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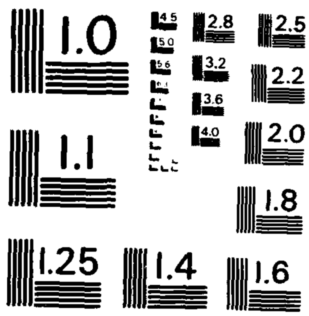

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Recent efforts to build computer simulation models of mental imagery have suggested that imagery is not a unitary phenomenon. Rather, such efforts have led to a modular analysis of the image generation process, with separate modules that can activate visual memories, inspect parts of imaged patterns, and arrange separate parts into a composite image. This idea was supported by the finding of functional dissociations between the kinds of imagery tasks that could be performed in the left and right —

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cerebral hemispheres of two patients who had had their corpus collosa surgically severed. The left hemisphere in both subjects could inspect imaged patterns and could generate single and multi-part images. In contrast, although the right hemisphere could inspect imaged patterns and could generate images of overall shape, it had difficulty in generating multi-part images. The results support the computational model, and suggest a deficit in the module that arranges parts into a composite. The observed pattern of deficits and abilities implied that this module is not used in language, perception, or drawing. Furthermore, the results suggest that the basis for this deficit is not a difficulty in simply remembering visual details or engaging in sequential processing.

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A COMPUTATIONAL ANALYSIS OF MENTAL IMAGE GENERATION: EVIDENCE FROM FUNCTIONAL DISSOCIATIONS IN SPLIT-BRAIN PATIENTS

Visual mental imagery is a transitory event. Images seem to come and go, and for many people only come to mind when they try to answer questions like, What shape are a Beagle's ears? Which is larger, a goat or a hog? Or, how would your sofa look against the opposite wall in your living room? Introspection is adequate to alert one to the fact that an object or scene is present in an image, but falls short of telling one how such images are created. In this paper we develop and test a theory of how visual mental images are generated.

One of the major advances of contemporary cognitive psychology is that phenomena previously treated as undifferentiated wholes have been broken into parts. For example, "memory" is now treated not as a unitary phenomenon, but as consisting of a set of processes that work in concert (encoding, search, comparison, etc.). The parts of such theories often correspond to distinct "processing modules," each of which performs a specific set of tasks within the context of the system as a whole. Kosslyn & Shwartz (1977; see Kosslyn, 1980) proposed a theory of the processing modules used in generating visual mental images, which is described below.

The Kosslyn & Shwartz theory was shaped in large part by three classes of empirical findings: First, although images introspectively may seem to pop into mind all of a piece, we now know that this is not so. In numerous experiments, researchers have found that the time to form an image increases

proportionally for each additional part of the imaged object or scene. For example, Beech & Allport (1978), Kosslyn, Reiser, Farah & Fliegel (1983), and Paivio (1975) found that people require an additional increment of time to form images of scenes for each additional object included in the scene. In addition, Kosslyn et al found that time to form an image of a geometric pattern increases when the number of "units" comprising the pattern increases, with "units" being defined by the Gestalt laws of proximity, similarity, good continuity, and other factors (see Kosslyn, 1980, chapters 4 and 6 for a review of the relevant literature). In short, images are not simply retrieved all at once, but can be built up on the basis of separately-stored encodings.

Second, the results of other experiments indicate that people can construct images by making use of descriptions of how parts are to be arranged. For example, subjects in one experiment could imagine a frying pan floating six feet above a bicycle which is six feet to the right of a rabbit (see Kosslyn et al., 1983). Once the image was formed, the time to scan between objects in it increased for objects that should be imaged further apart--providing evidence that people really can use descriptions to guide placement of the parts (see also Beech & Allport, 1978).

Third, Bundesen & Larsen (1978), Farah & Kosslyn (1981), Hayes (1973), and Kosslyn (1975) showed that people can form images at different "subjective sizes" (i.e., so they seem to subtend different visual angles). In general, less time is required to imagine objects at smaller sizes than large sizes, presumably because parts of objects are omitted at smaller sizes because of "grain" constraints (see chapter 5 of Kosslyn, 1980). This interpretation is consistent with the finding that, once an image has been formed, more time is

required subsequently to "see" a part of the object if it was imaged at a small size (subjects report having to "zoom in" to "see" parts at the smaller sizes; see Kosslyn, 1980).

Given these empirical findings, computational considerations place additional constraints on a theory. That is, as a heuristic for formulating a theory of information processing it is useful to consider what one would need to do to program a computer to mimic the effects observed with humans. Given that people can generate images at all, we need a processing module that can locate an encoding of an object or part's appearance stored in long-term memory, and can use this encoding to generate the corresponding image. Kosslyn & Shwartz call this the PICTURE processing module. This module is presumably used iteratively when an image is constructed from more than one stored part, with each part being generated separately (and thus image generation times increase with increasingly complex objects or scenes).

In addition, given that people can use descriptions to arrange separately-stored encodings (e.g., of a rabbit and a frying pan) into a single imaged scene, we need a processing module that interprets the relations (e.g., "six feet above") and sets the PICTURE processing module so that the objects are imaged in the correct locations. Kosslyn & Shwartz call this the PUT processing module. Given that people can form images at different "sizes" and "locations," and that objects or parts are imaged individually, the PUT module cannot simply place parts in absolute locations. Rather, parts must be placed in a specific relation to other previously-imaged parts, which themselves may appear at different sizes and locations. The PUT module must first locate one object or part before being able to place the next in the correct relative

location.

Thus, a third processing module is needed to locate objects or parts already in the image, and then to provide this information to the PUT processing module. Kosslyn & Shwartz call this the FIND processing module. This module identifies spatial patterns as depicting specific parts or objects. That is, the FIND processing module corresponds to the "inspection" routine. The FIND module can only classify patterns correctly when their shapes are discriminable, and if objects are imaged too small they will fail to be "visible" to the FIND processes. This module is presumed to be used not only in locating where to-be-imaged parts belong in relation to previously-imaged ones, but also when one "inspects" an image for a specific property (as in the examples that opened this paper) or even when one inspects an actual, visible object during perception. There are ample data supporting the idea that the same visual inspection mechanisms are used in perception and imagery (for reviews see Finke, 1980; Finke & Shepard, in press; Kosslyn, 1980, 1983; Segal, 1971; Podgorny & Shepard, 1978).

In summary, computational considerations formulated in light of the empirical findings lead to a theory that posits a PICTURE processing module that activates stored visual information, a PUT processing module that looks up and interprets a description of how parts are to be arranged (e.g., "the bicycle is six feet to the right of the rabbit"), invokes the FIND processing module to locate the "foundation part" (i.e., the part to which the to-be-imaged part is relative--"rabbit" in this case), and then uses this information in conjunction with the description of the relation ("six feet to the right") to set the PICTURE processing module so that the two images are

correctly arranged.

Functional dissociations

Although the Kosslyn & Shwartz theory of image generation is consistent with the empirical findings and computational constraints, it is not the only possible theory. For example, the functions carried out by the putative PICTURE and PUT modules might in fact be carried out by one single module, as might the functions putatively carried out by the PICTURE and FIND modules. If the PICTURE, PUT, and FIND processing modules are in fact distinct, we might expect to find evidence of functional dissociation following brain damage. That is, we may find cases in which some subset of the modules operates while another subset has been disrupted. In addition, by examining the nature of the deficits, we can begin to discover how the internal workings of the modules actually operates.

This "modular" approach to theorizing about imagery is especially appealing given Ehrlichman & Barrett's (1982) recent review of imagery deficits following brain damage. They discovered that imagery deficits cannot be consistently identified with damage to one cerebral hemisphere or the other, which is not surprising if the kind of analysis we offer is correct: If imagery in fact consists of a number of separate components, then the nature of the imagery task will be critical because different components will be used in different tasks. Furthermore, it is possible that different components are localized in different places in the brain (cf., Farah, in press). Thus, depending on the task and the localization of the relevant processing modules, different patterns of "imagery deficit" will be observed following brain damage.

The split-brain patient offers a unique opportunity to examine many of these issues. It has recently been shown in the special group of split-brain patients with right hemisphere language that the two hemispheres possess strikingly different cognitive capacities. The left hemispheres are essentially normal. In contrast, right hemispheres exhibiting good semantics, and right hemispheres exhibiting both semantic and syntactical skills and speech are still strikingly impaired on carrying out simple cognitive tasks such as elementary math, making inferences, and solving simple geometry problems. The possession of language ability in a half brain does not imply a concomitant ability to engage in other kinds of cognitive processing (see Gazzaniga & Smylie, 1984). Accordingly, it is of clear interest to examine whether a brain system that has basic language functioning might be impaired in generating mental images.

If the theory outlined above is correct, the PUT processing module involves looking up and using descriptions of how parts are arranged together, which involves the manipulation of symbolic representations. Many of the deficiencies in the right hemisphere can be considered to be deficiencies in manipulation of symbolic representations, and thus it seemed reasonable to ask whether there is a selective deficiency in the PUT module in the right hemispheres of these patients. On the other hand, we had no reason to suspect that the PICTURE or FIND processing modules would be impaired in either isolated hemisphere of our patients. Indeed, given that the perceptual abilities of both hemispheres are essentially normal, we had reason to suspect that the FIND module, which purportedly is also used to categorize perceptual input (see Kosslyn, 1980), would be intact in both hemispheres.

Plan of the paper

This paper has three major sections, each of which builds on the preceding ones. In the first section we document that the right hemisphere has a deficit with a task that requires all three imagery processing modules. We argue from the pattern of results here for a dissociation between the FIND processing module and the PICTURE and/or PUT modules.

In the second section we implicate the PUT processing module in the right hemisphere's deficit. In so doing, we demonstrate that the patient can form and inspect images very well in his right hemisphere, provided that the images are formed on the basis of only a single part. The deficit, we will argue, is in constructing multi-part images.

In the third section we switch to a second patient, whose right hemisphere has different abilities than the first patient's. We now attempt to show that the deficit implicates a specific type of mechanism which is used in image generation.

I. A RIGHT HEMISPHERE IMAGERY DEFICIT

The first set of experiments reported in this paper are designed to discover whether there is an imagery deficit in our first subject's right hemisphere. Discovery of such a deficit would implicate at least one functional dissociation, given the abilities that have already been documented in this patient's right hemisphere. Of particular interest, however, is the fact that this patient's right hemisphere has been found to have intact perceptual abilities. Indeed, it is actually better than the left hemisphere at recognizing faces (Gazzaniga & Smylie, 1984). These results suggest that the FIND processing module is intact in both hemispheres. Thus, as we will

document later in this paper, an imagery deficit in the right hemisphere will implicate difficulties in using the PICTURE and/or the PUT module.

Experiment 1

Consider the following task: Which upper case letters of the alphabet have only straight lines, and which have some curves? This task introspectively seems to require imagery, and in fact was used by Coltheart, Hull & Slater (1975) in their investigation of sex differences in imagery. In addition, it seems to involve images of a particular sort: When you image an upper case "A", for example, you do not image a specific letter you once saw (e.g., on page 3 of yesterday's New York Times). Rather, it seems as if one images a connonical, typical "A." Our claim here is that because literate adults have seen letters so many thousands (millions?) of times, varying in size, font, weight and so on, we have come to abstract out and store a "prototypical image" of the letter. According to pevious work on image generation, patterns stored in long-term memory are "parsed" according to the Gestalt laws of organization and the like, which leads us to posit that these prototypes are stored as collections of segments with descriptions of how the parts are arranged (see Kosslyn et al, 1983).

If this theory is correct, then all three image generation processing modules will be used when we image a letter: the PUT module will be necessary to interpret the description of how lines are to be arranged, and it will set the PICTURE process appropriately so that it can activate images of line segments in the correct positions. Furthermore, the PUT module will make use of information delivered by the FIND processing module in the course of computing the correct positions for each succeeding line. For example, in

generating an "A" one diagonal line would be imaged by the PICTURE process, the PUT processing module would arrange for a second diagonal line to be placed correctly by using the FIND processing module to locate the top of the first line and then using the description of the relation to set the PICTURE processing module so that the second line is imaged connected to the top, and so on.

Note that we are making two critical assumptions in using the straight/curved judgment task to test the theory of image generation: First, we are assuming that imagery is in fact used to perform this task. Second, we are assuming that images of letters are generated a segment at a time, requiring the PUT processing module to arrange the segments correctly. Both of these assumptions are defended in the Appendix.

We were encouraged to use a letter-classification task to study functional decomposition of image generation because of the findings of Farah, Gazzaniga, Holtzman & Kosslyn (submitted). They asked patient JW, who was tested in the first experiments reported in this paper, to evaluate from memory the relative heights of lower cases letters of the alphabet. For example, the lower case versions of "B," "D," "F" are relatively high whereas the lower case versions of "A," "C," "E" are relatively low. Weber & Bach (1969) introduced this task and took it to require imagery, although they provided no independent justification for this inference. We found that JW could not make the relative height judgments in his right hemisphere. However, this result could indicate a deficit in that hemisphere in the PICTURE, PUT, and/or FIND modules, in a generalized image generation module (if our breakdown is incorrect), a deficit specific to letters, a deficit for linguistic materials, a deficit in the

ability to hold images in mind over time, and/or a deficit in understanding the instructions. In the experiments in this section of the paper we whittle away the various counter explanations and examine the image generation process per se.

In this first experiment, we gave the straight/curved letter classification task to a person who had previously undergone surgical transection of his corpus callosum as a theraputic intervention for the control of otherwise intractible epilepsy. The subject stared straight ahead while lower case letters were presented to the left or right visual field, which ensured that only the right or left hemisphere received a letter on a given trial.

Method

Subject

The subject in the first set of experiments was JW, who has been extensively described elsewhere (Gazzaniga et al, 1984; Gazzaniga & Smylie, 1984; Sidtis et al, 1981). Briefly, JW is a right-handed 30 year old male who suffered from intractible epilepsy since the age of 19, and underwent corpus collosumectomy in 1979. When he was 13 years old he suffered concussive head trauma, without skull fracture, which led to brief, infrequent "absence spells." At age 18 he graduated from high school. At age 19 he had a major motor seizure. An EEG revealed irregular polyspike and high voltage repetitive 3 cps spike and wave bursts during sleep. These abnormalities has a right anterior temporal lobe prominence. Medication was unable to control his frequent seizures and absence attacks during the ensuing years. He was referred to Dr. D. H. Wilson at the Dartmouth-Hitchcock Medical Center, where

he underwent the two stage microneurosurgical section of his corpus callosum over the summer and fall of 1979. The posterior callosum was severed first. The anterior commisure was left intact.

When he was given a neurological examination 8 months after the completed operation, JW was found to be normal and of normal IQ. When we tested him he was oriented, alert, and conversed easily about present and past events. He had a good sense of humor and a quick wit. Following recovery from surgery, it was demonstrated that his left cerebral hemisphere was for all intents and purposes normal; his right hemisphere could comprehend most statements but could not speak. For present purposes, it is important to note that his right hemisphere can comprehend word-meanings, and has been shown to be able to understand relatively sophisticated instructions: For example, the right hemisphere can classify named objects in terms of super and subordination, can judge synonymy and antynomy, and can use a pre-cue to direct his eye movments (see Holtzman & Gazzaniga, 1984; Sidtis et al., 1981).

Materials

Five upper case letters containing only straight lines (Z, K, M, T, F) and five containing some curved lines (O, J, R, B, D) were selected at random from the alphabet. The lower case versions of these letters were randomized such that each one appeared twice in each visual field; the order of presentation in the two fields was also randomized.

Procedure

The subject sat before a CRT, fixating on a dot located in the center of the screen. A lower case letter of the alphabet was presented 1.5 degrees to the left or right of fixation for 100 msec, preventing eye movements and

ensuring that only one hemisphere could see the stimulus. Two buttons were placed directly in front of him, one 3 in. to the left of the other. The subject rested his left hand midway between the buttons and responded by lifting his arm and pressing a button with his left hand. (Ipsilateral and contralateral fibers allow both hemispheres to control gross arm movements, although the right hemisphere has an advantage when the left arm is used). The subject was to press one button if the <u>upper case version</u> of the letter had only straight lines (this button was labeled by a straight line) and another button if the upper case version had any curved lines (this button was labeled by a curved line).

The subject judged three successive blocks of forty trials each, with approximately five minutes rest between them. The CRT was connected to an APPLE II Plus microcomputer, which recorded both responses and response times.

Results

Response time and accuracy data were analyzed in separate analyses of variance. For the accuracy data we pooled the responses for the two replications with the same item and scored each item as 1, .5, or 0, depending on whether it was correct on both, one, or neither trial.

The results are presented in Figure 1. As is evident, the right hemisphere was significantly less accurate than the left (100% vs. 70% accuracy), $F(1, 8) = 6.48$, $p < .04$. In addition, judgments of curved stimuli were more accurate than judgments of straight stimuli (98% vs. 72%), $F(1, 8) = 5.12$, $p = .054$, but this effect was different for the two hemispheres, as indicated by an interaction between response and hemisphere, $F(1, 8) = 5.12$, $p = .054$. This interaction reflected the fact that the left hemisphere made no

errors for either response whereas the right was accurate 97% vs. 43% for curved and straight stimuli, respectively. This difference in accuracy probably reflects nothing more than a response bias. No other effect or interaction was significant, $p > .17$ in all cases.

The results from the response times tell a different story. The right hemisphere was significantly faster than the left, $F(1, 8) = 7.09$, $p < .05$. This finding may simply reflect the greater control of the right hemisphere for the left handed motor response required in this task. However, a glance at the two panels of Figure 1 reveals that the faster times in the right hemisphere result in the appearance of a "speed/accuracy tradeoff" in the data: one could argue that the right hemisphere may simply have been guessing on a higher proportion of the trials in order to make rapid responses. In addition, judgments of curved stimuli were faster than judgments of straight ones, $F(1,8) = 6.79$, $p < .05$, and now there was improvement over the blocks of trials, $F(2,16) = 6.30$, $p < .01$. There was no difference in times for the first or second replication within a block, $F < 1$. The only significant interaction was between blocks, hemisphere, and stimulus type, $F(2, 16) = 4.19$, $p < .05$. The right hemisphere was faster than the left for both stimulus types in the first two blocks, and for straight stimuli in the third block; the left was faster than the right only for judgments of curved stimuli in the third block. This result is further indication of a "speed/accuracy tradeoff" for the first two blocks and for the straight stimuli in the third block, where the right hemisphere was faster than the left: At the same time the right hemisphere was being faster, it committed more errors for these responses. This pattern of responses was also reflected in a marginally-significant interaction between

hemisphere and stimulus type, $F(1, 8) = 3.56$, $p = .1$. No other interaction approached significance, $p > .2$ in all cases.

INSERT FIGURE 1 HERE

Discussion

As expected, the right hemisphere was less accurate than the left. However, the relationship between the speed of responding and errors suggested that the right hemisphere may not have been careful in its judgments: in this experiment, it could have been guessing so as to respond faster (although this account will not prove sufficient to explain the right-hemisphere deficit in all subsequent experiments). In addition, there is evidence that the right hemisphere had a bias to respond "curved." This is not an unreasonable strategy, we realized, given that about 70% of the curved lower case letters also had curved upper case versions--which may explain why the right hemisphere performed at better than chance levels.

Before we can infer that JW's relative difficulty in performing the task in his right hemisphere implicates an image generation deficiency, we must rule out a host of counter explanations. In order to perform the task one must: 1) be able to read the lower case cue; 2) understand that the cue directs one to access information about the upper case version; 3) generate an image of the upper case version; 4) maintain the image long enough to evaluate it, and, 5) evaluate the lines in the upper case letter, making a curved/straight judgment. Furthermore, one must understand what the task requires, and one must be able to put these steps together to perform the task as a whole.

In Experiments 2 through 6 we attempt to systematically eliminate the alternative explanations of the failure of JW's right hemisphere to perform the task well. In each case we consider the possibility that the right hemisphere is deficient at some component of the straight/curved task other than use of one (or more) of the imagery processing modules, and we assess the right hemisphere's ability to use that component in another task.

Experiment 2

In this experiment we asked our subject to perform a perceptual analogue of the imagery task. The subject briefly saw upper case letters and made the straight/curved judgment on the basis of what he saw. Immediately following this control task we repeated the letter cue task, urging the subject to be accurate and looking to see if practice at making the judgment improved performance in the imagery task.

This experiment will serve two purposes: First, it will serve as a control, allowing us to demonstrate that the right hemisphere can understand the instructions and can perform the classification. Second, if we do find that the right hemisphere can perform the perceptual task but not the imagery analogue, this will start us on our way toward discovering functional dissociations among the processing modules. That is, according to the theory, the FIND processing module is used when one inspects both images and percepts. Thus, if we find that the subject's right hemisphere can perform the perceptual task but cannot perform the analogous imagery task, we are encouraged to pursue possible dissociations among the image generation processing modules.

Method

<u>Materials</u>

The upper case versions of the letters were substituted for the lower case ones used in the previous experiment. Other than this substitution, the materials were identical to those used earlier.

Procedure

The procedure was identical to that used in the previous experiment except that the subject was asked to judge the letters as they actually appeared, not the other-case versions.

Two blocks of 40 trials were used, with again approxiately five minutes rest between blocks.

Results

In contrast to the results from the previous experiment, both hemispheres did quite well on this task. The left and right hemispheres had 100% and 97.5% accuracy, respectively, $F < 1$, and there were no effects of blocks (100 vs. 97.5% correct for blocks 1 and 2, respectively) or type of response (100 vs. 97.5% for curved and straight, respectively), $F < 1$ in both cases. No other effects or interactions were significant in the error data, $p > .25$ in all cases.

The response times revealed the same pattern as did the error rates: There was no effect of hemisphere (.877 vs. .876 sec. for left vs. right hemisphere) or response type, $F < 1$ in both cases. In fact, the only significant results were due to block (.923 vs. .830 sec. for block 1 and 2, respectively), $F(1, 8) = 6.98$, $p < .05$, and the interaction between hemisphere, response and replication was marginally significant, $F(1, 8) = 4.17$, $p < .09$. This trend reflected the fact that only for curved stimuli in the left hemisphere were times on the second replication faster than those on the first

replication; in the three other cases, times were slighly slower on the second replication. No other effect or interaction even approached significance, $p > .25$ in all cases.

Lower case cue task

We simply repeated the original letter-classification task, again showing lower case letters and asking for straight/curved judgments on upper case versions. The materials were identical to those used in Experiment 2 and the procedure was identical to that used in Experiment 2. One block of 40 trials was administered.

Results Again, the left hemisphere performed strikingly better than the right, 100% compared to 65% accuracy, $F(1, 8) = 7.0$, $p < .05$. In addition, there was a tendency for more errors with straight letters (70% vs. 95% for curved letters), $F(1, 8) = 3.57$, $p = .1$, and there was a tendency for especially poor performance for straight letters for the right hemisphere, as witnessed by a marginally-significant interaction between stimulus type and hemisphere, $F(1, 8) = 3.57$, $p = .1$: whereas the left hemisphere was perfect, the right was correct on 90% of the curved trials and only 40% of the straight ones. This pattern of responses, which was also apparent in the previous experiment, suggests a bias to respond "curved" in the right hemisphere.

Unlike the error data, there were no differences in any of the comparisons of response times: Times were .973 sec and .949 sec for the left and right hemisphere, respectively, $F < 1$; .905 sec and 1.016 sec for curved and straight letters, respectively, $F(1, 8) = 1.99$, $p > .25$; and .948 sec and .974 sec for replication 1 and 2, $F < 1$. No other effect or interaction approached significance, $p > .25$ in all cases. The major results from both

tasks are illustrated in Figure 2.

INSERT FIGURE 2 ABOUT HERE

<u>Discussion</u>

Both hemispheres clearly understood the perceptual control task and clearly could perform it. In fact, both did so well that a "ceiling effect" occurred, preventing us from making any comparisons about the relative efficacy of the hemispheres on this task. But this was not our purpose: we now had reason to expect that the right hemisphere would understand the classification task, yet nevertheless, performance in the imagery task was still very poor in the right hemisphere. Again, the pattern of errors suggested that there was a bias to respond "curved." Most lower case letters are themselves curved, and it is possible that the subject was basing his judgments in part on the way the actual stimuli appeared. This is in fact not a bad strategy given the "straight" letters we used, z, k, m, t, and f; two of these have only straight lines in lower case, and in fact z and k were judged correctly on both replications by the right hemisphere. Indeed, all but one of the errors made here (to "d") can be explained simply by assuming that he was using the lines in the lower case stimuli as cues. The next experiment tests this account of the right hemisphere deficit in the straight/curved imagery task.

Experiment 3

The pattern of errors in the previous experiment suggests that the curved lines of the lower case cues may have presented a "Stroop test" situation for the right hemisphere, where what JW saw interfered with image

generation or response. In this experiment we used auditory presentation of the stimuli, eliminating the possibility of interference from the lower case visual cue or of his using the shape of the stimuli to help make the judgment. Furthermore, the nature of the response was made compatible with the straight/curved judgment itself, as will be described shortly, which allow us to rule out a Stroop-type response conflict.

Methoc

Materials

New letters were selected for this task. The letters with some curves in the upper case versions were G, J, D, B, and Q; the letters with only straight lines in the upper case versions were A, M, H, T, and E. These letters were selected so that half of them (roughly equally divided between the two judgments) had a vertical line on the extreme left of the letter; this property will be important for later experiments that make use of this letter set. A list of the letters was prepared, with each letter being presented twice on left-hemisphere trials and twice on right-hemisphere trials. The letters and field of presentation were randomly ordered.

In addition, in this experiment the cues presented on the CRT were the pair "X 0" and "0 X." Each pair was presented 10 times in each visual field (1.5 degrees to either side) for 100 msec, with the presentation order and field being coordinated with the list of letters so that each letter occurred once with each pair in each visual field.

Procedure

The subject again began by staring at the fixation dot. Now, however, he heard the name of one of the letters. He was told to make his judgment and

then to look for the "X 0" or "0 X" pair. If the letter had only straight lines, he was to point at the location on the screen where the "X" had appeared; if the letter had curves, he was to point where the "0" had appeared. The cue was presented approximately 2 sec after the letter was named, and the subject seemed to have no difficulty in understanding that he was to point to the location of the X or 0 as appropriate. All pointing was done with the left arm. Three blocks of trials were conducted, each having 40 trials.

Results

Because of the methodology employed it was impossible to collect response times. The error rates, however, revealed the now-familiar pattern: The left hemisphere did very well, making correct judgments on 95% of the trials, whereas the right hemisphere did very poorly, making correct judgments on only 52% of the trials, $F(1, 8) = 16.9$, $p < .005$. There also was a significant interaction between block, hemisphere, and response, $F(2, 16) = 6.32$, $p < .01$: In the right hemisphere, increasingly more errors occurred with curved stimuli on the later blocks whereas increasingly fewer errors occurred with straight stimuli. This interaction suggests a shift from the bias to respond "curved" to a more even-handed guessing strategy. There was no systematic tendency to respond on the basis of the appearance of the lower case version of the letter. No other effect approached significance, $p > .11$ in all cases.

Discussion

When the influence of the lower case cues themselves was eliminated, performance in the right hemisphere dropped to chance. This is just as would be expected if images simply could not be constructed in this hemisphere.

However, one might argue that the right hemisphere simply does not understand what we want or that it is incapable of performing multi-step tasks. Perhaps JW's right hemisphere is simply deficient at tasks that require more than one step.

Experiment 4

In this experiment we continue to attempt to eliminate alternative explanations for the right hemisphere's poor performance in the lower case cue task based on components of the task other than those used in image generation per se. We now performed another kind of perceptual control, which required the subject to view slides of pairs of letters. The upper and lower case versions of a letter were tachistoscopically presented side by side, and the subject was asked to pick out the upper case letter and to classify it as having all straight lines or some curves. Both letters were drawn at the same size, so size could not be used as a cue in the selection phase.

This task, then, provided a control for several of the steps in the imagery task. First, both hemispheres had to be able to understand what we meant in the instructions when we referred to upper case letters. Second, both hemispheres had to be able to select upper case letters per se. Third, the judgment had to be made following selection of a stimulus. Thus, if the subject's difficulty in the imagery task is in fact due to confusion about the appearance of the upper case letters, difficulties in making the judgment, or difficulty in integrating the two tasks together, then he should have difficulty in performing this task.

Method

<u>Materials</u>

Twenty letters of the alphabet were selected, half having upper case versions with only straight lines and half having upper case versions with curved lines. We did not use any letter that had the same-shaped upper and lower case versions. We prepared two slides for each letter, one with the lower case version to the left of the upper case version, and one with the lower case version to the right of the upper case version. The slides were prepared by drawing directly on acetate with a black felt pen, and the two letters on each slide were drawn at the same height and approximately at the same width. Slides were presented using a rear-projection screen, and the duration of exposure was controlled by a tachitoscopic shutter on the projector.

<u>Procedure</u>

Each slide was presented twice, one in each visual field. The slides were presented in a random order and field of presentation was randomized. As usual, the slides were 1.5 degrees to the left or right of a fixation point and were exposed for 100 msec. The subject was told to point to the area on the rear-projection screen that had displayed the upper case version of the letter, and then to press one button (the one labeled by a straight line) if the letter had only straight lines and the other button (labeled by an arc) if the letter had any curved lines. As usual, all responses were made with the left arm. Three blocks of trials were presented.

Results

The analysis of accuracy rates revealed that the right hemisphere was <u>more</u> accurate than the left (93% vs. 80%), $F(1, 8) = 5.57$, $p < .05$, that responses to curved letters were more accurate than responses to straight ones

(100% vs. 73%), $F(1, 8) = 7.64$, $p < .03$, and that these two effects interacted, $F(1, 8) = 5.57$, $p < .05$ (100% accuracy in both hemispheres with curved simuli, compared to 60% and 86.7% accuracy in the left and right, respectively, for straight stimuli). In addition, there was a tendency for the left hemisphere to do progressively worse over blocks while the right was relatively constant, $F(1, 16) = 3.37$, $p = .06$, and for this interaction to depend on the response, $F(1, 16) = 3.37$, $p = .06$. No other effect or interaction was significant, $p > .2$ in all cases.

The analysis of response times revealed a slightly different pattern: There was no effect of hemisphere (2.439 sec vs. 2.238 sec for left vs. right, respectively), $F(1, 18) = 1.14$, $p > .25$, nor of stimulus type, $F(1, 18) = 1.14$, $p > .25$. However, times were slowest on the second block, $F(2, 36) = 39.27$, $p < .001$, and times were faster for the second replication of a letter within a block, $F(1,8) = 8.03$, $p < .03$. The interaction between block, replication and stimulus type was also significant, $F(2, 16) = 3.54$, $p = .05$. Although the time to judge both types of stimuli decreased with successive blocks, straight stimuli showed more improvement over blocks. There was also a trend towards an interaction between block and stimulus type, $F(2, 36) = 2.55$, $p < .1$, suggesting a tendency for relatively faster responses to the straight stimuli in block 2, whereas responses were faster to the curved stimuli in blocks 1 and 3. No other effect or interaction was significant, $p > .15$ in all cases.

Discussion

Both hemispheres clearly quickly caught on to what was required in the task and could select and evaluate the upper case stimuli. In fact, the right hemisphere actually did better in this task; however, this result probably

reflects the right hemisphere's superior ability to make subtle perceptual discriminations, which was important here because so much information was presented at once. Thus, these results demonstrate that JW's right hemisphere is capable of selecting the proper letter, evaluating it, and putting the two steps together. However, one could still argue that the right hemisphere does not understand what we want in the imagery task. Thus, in the next experiment we attempt to train the hemisphere by providing feedback in our basic lower case cue task.

Experiment 5

Another remaining counterexplanation of the right hemisphere's failure on the straight/curved imagery task is that the right hemisphere simply does not understand what it is supposed to do when given the lower case cue in that task. In this experiment we first establish baseline performance in the lower case cue task. We then urge the subject to be cautious in responding and to consider his decisions carefully; following this, we provide feedback about accuracy of performance. The use of feedback is a way to provide the right hemisphere with examples of what we want, which in conjunction with the instructions should make the nature of the task as clear as possible. Finally, after we have the right hemisphere performing well, we switch to a new set of letters. If the improved performance following feedback is due to his finally understanding what to image, and this was the only problem all along, then we expect that his ability to perform the task will transfer to the new letters. However, if the improved performance is merely the result of the right hemisphere's memorizing stimulus-response pairs, then we would not expect transfer to new letters.

Method

Materials

The letters used in Experiment 4 were also used here. Now, however, the lower case versions of the letters were presented on the CRT. Each letter appeared twice in each visual field, with the order of presentation and field being randomized.

For the second set of trials, the "transfer trials," five new letters were selected that had upper case versions containing only straight lines: V, K, F, Y and N. Five new letters were selected that had lower case versions containing some curved lines: U, O, C, R, and S. Again, half of these letters had a vertical line on the left and half did not. (Due to the limited number of letters of the alphabet, some of these lower case cues resembled the upper case ones; the possible effects of this factor can be examined directly in the data, however.) As usual, each lower case version was presented to each visual field twice, and the order of presentation and field was randomized. Three blocks of 40 trials were administered.

Procedure

The procedure for the first four blocks was identical to that of Experiment 2 in all respects but two: First, during the second block we cautioned the subject to be careful and to review the judgment in his head before actually making a response. We reminded the subject of the need to be careful about five times during the session, but did not make this reminding contingent on correct or incorrect performance on the trial preceding the admonition. Second, in the third and fourth blocks of trials, we provided the subject with feedback after each trial simply by saying "right" or "wrong"

aloud.

The procedure for the three "transfer" blocks, using the new letters, was identical to that of the first block, with no feedback or special encouragement. The subject was tested on the transfer task *immediately* following the previous one (separated only by a rest period of approximately 15 minutes).

Results

Initial trials.

Figures 3 presents the accuracy rates and response times for the first four blocks. We began by analyzing the first two blocks, where no feedback was provided. We again found that there was greater accuracy in the left hemisphere, $F(1, 8) = 11.25$, $p = .01$, and that there was a slight tendency for greater accuracy with curved stimuli, $F(1, 8) = 3.86$, $p < .1$. To our surprise, there was a significant interaction between block, hemisphere, and response, $F(1, 8) = 8.33$, $p < .03$. As is apparent in Figure 4, this interaction seems to reflect primarily the degraded performance for curved stimuli in the right hemisphere during the second block. This interaction may reflect a gradual abandoning of his response bias in favor of a simple guessing strategy. No other effects or interactions were significant in this analysis, $p > .25$ in all cases.

A slighly different pattern is evident in the response times: There was a distinct increase in time on the second block, $F(1, 8) = 42.46$, $p < .001$, which probably reflects our urgings to be careful; there was no effect of hemisphere, $F(1, 8) = 2.24$, $p > .1$; there was no effect of stimulus type, $F < 1$, or of replication, $F(1, 8) = 2.38$, $p > .1$. In fact, the only other significant

comparison was an interaction between hemisphere and block: the right hemisphere began by being faster than the left, and exhibiting the kind of "speed/accuracy tradeoff" we saw in Experiment 1. But by the second block, however, the right hemisphere is taking longer than the left--but is still committing more errors than the left hemisphere. No other effect or interaction was significant, $p > .25$ in all cases.

The effects of feedback are apparent in blocks 3 and 4. By block 4 there is no significant difference in accuracy between the hemispheres, 100 % for the left and 90% for the right, $F(1, 8) = 1.0$, $p > .25$, and there is no significant difference in response times, 1.172 sec for the left and 1.248 for the right, $F < 1$. However, the left hemisphere was faster on replication 1 than on replication 2, while vice versa for the right hemisphere, $F(1, 8) = 5.83$, $p < .05$ for the interaction of replication and hemisphere, and curved stimuli were judged faster on replication 1 than on replication 2, but vice versa for straight stimuli, $F(1, 8) = 5.25$, $p = .05$ for the interaction between replication and response. Finally, there was a tendency for responses to curved stimuli to be faster than responses to straight ones, $F(1, 8) = 3.48$, $p = .1$, and no other effect or interaction approached significance, $p > .2$ in all cases.

An analysis of all four blocks together revealed that accuracy improved over the blocks, $F(3, 24) = 3.27$, $p < .05$, that the left hemisphere was more accurate than the right, $F(1, 8) = 17.6$, $p < .01$, and that over successive blocks responses to straight stimuli improved more than those to curved stimuli, $F(3, 24) = 2.76$, $p = .06$ (this may simply reflect a ceiling effect for curved stimuli, however).

In addition, considering all of the data together revealed that there were differences in the overall time per block, $F(3, 24) = 59.9$, $p < .001$ (the subject slowed down on block 2, then sped up on each block thereafter); that the left hemisphere was generally faster than the right, $F(1, 8) = 6.69$, $p < .05$, and that there was a significant interaction between the difference in the response times for the two hemispheres over blocks, $F(3, 24) = 3.97$, $p < .03$. No other effect or interaction was significant, $p > .25$ in all cases.

INSERT FIGURE 3 HERE

Transfer trials.

The results from this condition are presented in Figure 4. As is evident, there was virtually no savings in the right hemisphere in terms of accuracy: The overall accuracy of the two hemispheres was 95% and 66.7%, for the left and right respectively, $F(1, 8) = 4.90$, $p = .058$. There was a tendency for improved performance in later blocks, $F(2, 16) = 2.80$, $p < .1$, but no other effect or interaction approached significance, $p > .25$ in all cases.

The response times are evident on the right side of Figure 4. As is apparent, there was no overall difference in times for the two hemispheres, $F < 1$. In addition, times again varied with block, $F(2, 16) = 3.81$, $p < .05$. Again, there was an apparent speed/accuracy tradeoff on Block 2. Not illustrated in the figure, there was a marginal trend for faster responses for the second replication (1.672 sec vs. 1.427 sec), $F(1, 8) = 4.19$, $p < .08$. (This is of some interest because the only other time we observed an effect of replication was at the very beginning with our original letters.) No other

effect or interaction was significant in this analysis, $p > .25$ in all cases.

To better assess possible savings on the transfer trials, we performed analyses directly comparing performance on the last three blocks of the transfer trials with performance in the first three blocks of the initial trials. An analysis of the accuracy data indicated that there was no overall savings on the transfer trials, $F < 1$, and that the relative difference in the performance of the hemispheres was the same in the two conditions, $F < 1$. In fact, the only difference between the conditions was that accuracy improved with successive blocks in the initial trials (due to the feedback), whereas it improved only marginally with successive blocks in the transfer condition, $F(2,32) = 3.30$, $p < .05$. For all other interactions involving condition, $p > .25$.

The analysis of all of the response times indicated that there was only a marginal difference between the overall times for the two conditions, $F(1, 16) = 3.88$, $p < .08$, and revealed only two significant effects of condition: As is evident in Figure 5, the effects of block were different in the two conditions, $F(2, 32) = 44.39$, $p < .001$; in addition, this interaction itself was different in the two hemispheres, $F(2, 32) = 3.29$, $p = .05$. The difference between the hemispheres steadily decreased in the initial trials, whereas it was largest in the second block for the transfer trials and actual reversed (with the right hemisphere becoming faster) for the third block (this indicates a speed/accuracy tradeoff). Apparently, the right hemisphere realized the increased difficulty on the second block of the transfer trials, but then did not try very hard on the third block. No other interactions involving condition approached significance, $p > .25$.

<u>Discussion</u>

In the initial blocks of trials, the subject's right hemisphere again was unable to make the shape judgments from memory. However, when given feedback about accuracy, this hemisphere quickly learned to perform the task. Given this evidence that the right hemisphere had finally understood what we wanted it to do, the question became whether it could generate the images to perform the task, or had simply memorized the responses to the letters. The transfer task addressed this question. The results of this task were clearcut: the right hemisphere of this patient had not learned to perform the imagery task. The right hemisphere was once again at near-chance performance. In fact, when the data were examined carefully, the slightly-better than chance performance could be attributed to the letters c, o, and s, which have similar-shaped upper and lower case versions.

Experiment 6

The final experiment in this series with patient JW examined one last way in which his right hemisphere could fail to perform the task but not because of an image generation deficit. So far we have demonstrated that JW's right hemisphere can read a cue in one case and pick out the corresponding other-case letter (see Farah et al, submitted) and can select the upper case version when it is next to the lower case one, both of which involve reading the letters and accessing a stored representation of the cases. We have also shown that JW's right hemisphere can perform the correct judgment on perceptual stimuli and can integrate multiple steps together in similar tasks. And we have shown that the problem is not due to this hemisphere only classifying what it sees or being disrupted by conflicting visual input. A remaining weak link

preventing us from inferring an image generation deficit, then, is that we have not demonstrated that the right hemisphere can evaluate an _image_ of upper case letters. Perhaps the right hemisphere can _generate_ images but cannot maintain them long enough to make the judgment. Or perhaps images are dimmer than percepts, and the FIND module in the right hemisphere has less acuity than in the right hemisphere and so cannot effectively classify these dimmer patterns.

Thus, in this experiment we show that JW's right hemisphere can perform the straight/curved judgment on images, except that the images he uses in this task are not _generated_ from long-term memory, but instead are simply retained from external input. That is, according to the theory, images can be evoked either by generating them from information stored in long-term memory, as has been discussed thusfar, or by briefly retaining on-line perceptual input. The theory posits a LOAD module that squelches subsequent sensory input (which usually disrupts prior percepts) so that a perceptual pattern can be retained briefly as an image; it also posits a REGENERATE module that maintains an image in short-term memory for a brief period, keeping it available for further inspection (see Kosslyn, Brunn, Cave, & Wallach, in press, for a concise summary of the overall imagery theory).

Method

Materials

Twelve three-letter words were created, using only letters included in the second and third lists used in the previous experiments. The words were constructed so that an upper case letter with only straight lines or with some curves appeared equally often as the first, second, or third letter of the

words. One letter was selected from each word to be used as the "target" letter; target letters were identical to those used in the second list of letters used in the lower case cue task (first used in Experiment 3). Target letters were presented here in their upper case versions, and occurred equally often in each serial position of the words.

In order to prevent the subject from knowing where to focus on the screen to see a given letter, the words were entered into a computer such that they appeared one, two, or three spaces displaced towards the right from the "standard" angle of displacement from the fixation point (1.5 degrees). The amount of displacement was varied randomly, except that each amount appeared equally often over trials. Words were presented once to each visual field within a block, for a duration of 150 msec, and order of presentation and field was randomized.

Procedure

Two conditions were tested. The "cue-before" condition was intended as a baseline, given that this task contained all but the imagery components. In this task, the subject was given the cue "1", "2", or "3" before a word was presented. This cue told the subject that we wanted him to classify the first, second, or third letter of the word. Approximately 1 sec after the cue was given verbally, a word was briefly presented to one visual field or the other. The subject had to pick out the appropriate letter and classify it as having all straight lines or some curved lines, pressing buttons as usual. The "cue-after" condition differed only in that the cue was presented approximately 2 sec after the word was presented. Thus, in this case the subject had to maintain an image of the word, which he then used to select the proper letter

and make the classification. Note, even though the cues were given aloud, and hence were available to both hemispheres, the fact that the words were lateralized prevents both hemispheres from making the judgment.

Two blocks of each type of trial were presented, in the following order: cue-before, cue-after, cue-after, cue-before.

Results

Cue-Before

There were no significant differences in accuracies in the analysis of the cue-before data, $p > .18$ for all comparisons. Of note is the fact that the left hemisphere was accurate on 95.8% of the trials, compared to 87.5% for the right hemsiphere, $F(1, 10) = 2.0$, $p > .18$.

In contrast, the analysis of response times revealed that the right hemisphere was slower than the left (2.265 vs. 1.646 sec), $F(1, 10) = 13.18$, $p < .005$, that there was improvement with successive blocks (2.137 vs. 1.774 sec), $F(1, 10) = 7.33$, $p < .03$, and that there was a tendency for faster responses to curved stimuli (1.772 vs. 2.140 sec.), $F(1, 10) = 5.73$, $p = .04$. In addition, most of the improvement over blocks was with the straight stimuli, as witnessed by an interaction between block and stimulus type, $F(1, 10) = 5.18$, $p < .05$. No other effects or interactions approached significance, $p > .1$ in all cases.

Cue-After

Again, there were no significant comparisons in the analysis of the accuracy data, $p > .2$ in all cases. For the comparison of hemispheres, there was 95.8% accuracy in the left and 83.3% accuracy in the right, $F(1, 10) = 1.8$, $p > .2$.

The response times again were more sensitive to differences in the different conditions: Less time was required in the left hemisphere (4.018 vs. 4.769 sec), $F(1, 10) = 14.01$, $p < .005$, and times slowed down with block (4.023 vs. 4.763 sec), $F(1, 10) = 9.20$, $p < .02$. No other effect or interaction approached significance, $p > .25$ in all cases.

We also conducted analyses that included both the cue-before and cue-after data. This was desirable because the cue-before task has all processing components in common with the cue-after task except those involved in imagery processing. Thus, the cue-before results provide a baseline against which we can discover the extent to which the ability to maintain or inspect an image might be affecting performance in the straight/curved imagery task. There were no significant differences in the analysis of the accuracy data, but two comparisons came close: Hemisphere, $F(1, 10) = 4.31$, $p < .07$, and the block by hemisphere interaction, $F(1, 10) = 4.31$, $p < .07$ (with 100% and 91.7% accuracy for blocks 1 and 2 for the left hemisphere, and 79% and 91.7% accuracy for blocks 1 and 2 for the right hemisphere). Most important for present purposes, there was no hint of different effects of hemisphere in the two tasks, $F < 1$.

The analysis of response times revealed that times in the cue-before task were in general much faster than in the cue-after task (1.956 versus 4.393 sec), $F(1, 10) = 406$, $p < .001$, but this result is meaningless: The times in the cue-after condition include the approximately 2 sec delay before the cue was presented and the time to hear and comprehend the cue. In addition, whereas times decreased on the second block of the cue-before task (2.137 versus 1.774 sec), they increased on the second block for the cue-after task

(4.023 vs. 4.763 sec), $F(1, 10) = 16.88$, $p < .003$. For present purposes, however, it is important to note that the hemispheres performed the same way in both tasks, $F < 1$ for the interaction of hemisphere and task. And no other interaction with task was significant, $p > .12$ in all cases.

Thus, relative to the cue-before perceptual baseline, both hemispheres can perform the imagery task at equivalent levels.

Lower case cue task.

To ensure that the right hemisphere had not suddenly gotten the idea of what we wanted, we administered a block of the lower cue task, using the list and procedure of the trials of the first block of Experiment 6. The results were as usual: The left hemisphere was more accurate than the right (100% versus 60%), $F(1, 8) = 25.6$, $p < .001$. In addition, now straight stimuli were judged more accurately than curved ones (70% versus 90% correct), $F(1, 8) = 6.40$, $p < .04$, and this effect was due to the right hemisphere (100% for both types of stimuli for the left, 40 and 80% for curved and straight, respectively, for the right), $F(1, 8) = 6.40$, $p < .04$. Apparently, the right hemisphere now had a bias to respond "straight."

The only significant effect in the analysis of the response times was due to hemisphere: As usual, the left was faster (1.318 versus 2.032 sec), $F(1, 8) = 11.44$, $p < .01$. There was a trend for faster responses for curved stimuli on the second replication and faster responses for straight stimuli on the first replication, $F(1, 8) = 3.76$, $p < .09$, and no other effects or interactions were significant, $p > .35$ in all cases.

Discussion

A major distinction between the present task and the earlier one is

that an image did not have to be generated here, whereas it did before. Thus, the fact that JW can perform this task in his right hemisphere but not the earlier one is strong support for our inference that he has a specific image-generation deficit. When an image had to be maintained, both hemispheres performed the task as well, relative to the non-imagery baseline performance. In addition, even after performing well in the image inspection task JW still could not perform the image generation task in his right hemisphere. This fact is strong evidence that he is not simply having difficulty in performing a multi-stage imagery task.

It is of some interest that, for the right hemisphere, the cue-before task was not as easy as was the single-letter classification task used in Experiment 2. There are at least three possible accounts of this finding: (1) It may indicate that the right hemisphere had selective difficulty in picking out the cued letter; (2) that it had more difficulty encoding the words because the left-hand portion was less acute (it fell in the extreme left of the visual field), or (3) perhaps that the FIND module in the right hemisphere is less acute--but this deficiency was masked by ceiling effects in the previous Experiment 2. However, the results of Experiment 4 belie the third alternative, as do previous findings that right hemispheres usually have greater discriminability (e.g., see Springer & Deutch, 1981). In any event, the 83.3% accuracy observed for the right hemisphere in the cue-after task is strikingly better than the 60% accuracy observed in the lower case cue task--even though this task used the same target items as the cue-after task and followed immediately after that task.

The comparison between the cue-before and cue-after results allows us

to infer that the REGENERATE and LOAD processing modules are intact in JW's right hemisphere; if they were not, we would have found inferior performace in the cue-after task relative to the cue-before task (which required us of all of the same processing modules except those two). This finding leads us into the second part of the paper, where we attempt to decompose the image generation deficit itself.

II. DISSOCIATIONS AMONG PROCESSING MODULES

We have thusfar demonstrated that JW's right cerebral hemisphere has an image generation deficit: It cannot generate images of letters of the alphabet. In addition, however, we have shown that there is a dissociation between at least two of the processing modules putatively used in imaging letters, namely the FIND "inspection" module and the PUT and/or PICTURE modules. That is, in Experiments 2, 4, and 6 we showed that the right hemisphere can perform perceptual analogues of the straight/curved image generation task. Recall the FIND module is putatively used both in perception and in imagery. In addition, in the previous experiment we showed that when image generation was not involved, the right hemisphere could inspect images about as well as it could inspect the actual words, when--if anything--only a brief iconic memory was used.

However, we do not know which of the other two modules is responsible for the observed generation deficit in the right hemisphere. It could be that the PICTURE module produces only very faint, weak images, which cannot be used effectively. Or it could be that the PUT module is defective, preventing the segments of a letter from being arranged to form an image of the pattern. Or, perhaps both modules are deficient. In addition, we do not know if the deficit

is particular to images of letters and words, or is more general. The experiments in this section of the paper address these concerns.

Experiment 7

Our claim is that JW's right hemisphere cannot form images of letters of the alphabet because these images must be formed by composing together distinct parts. If so, then we have no reason to expect a deficit when images having only one part must be formed. The next question we asked was whether both cerebral hemispheres in our first patient could in fact generate images of global shapes. If so, we have evidence that the PICTURE processing module operates in both hemispheres of this subject.

The first task we used in this experiment required the subject JW to decide which of two similar-sized objects, such as a goat and a hog, was the larger. This task was chosen in part because Kosslyn, Murphy, Bemesderfer & Feinstein (1977) and Kosslyn (1980, chapter 9) had shown that images of the two shapes were used to make the judgment. They asked people to start off with a tiny image or a normal sized image of one object, and then to decide if another named object was larger than the first. Subjects were told that they did not have to use the image of the first object, but were simply to decide as quickly as possible. If the objects were similar in size, more time was taken if the first was imaged at a tiny size: subjects claimed that they had to "zoom in" on this object before they could compare it to the second one; if the first object was imaged at a normal size, no such "zooming in" was necessary, and hence less time was taken. For objects not similar in size, such as an elephant versus a rabbit, there was no effect of the size of the initial image and subjects claimed not to use imagery. These results make sense if objects are labeled in

memory in terms of size categories: An elephant is "large" and a rabbit is "small;" knowing this is enough to make the judgment. But two similar-sized objects are likely to be classified in the same category: A goat is "medium" and so is a hog; knowing the size categories does not help, and one is forced to use imagery to make the comparision (see Kosslyn, 1980, for a discussion of various theories of processing in this task).

In addition, we also tested JW in a second task that required subtle spatial distinctions, and hence was likely to evoke imagery: We gave him the names of common objects, and asked whether they were higher than they are wide.

Task 1

Method

Materials

The following animal names were used as stimuli: mouse, bat, rat, cat, datschund, beagle, spaniel, beaver, lamb, hog, goat, wolf, tiger, deer, bear, donkey, horse, zeebra, moose and elephant. These animals were to be compared to goat, with 10 being smaller and 9 being larger. Our subject lived on a farm and was interested in animals; as the data attest, he had little difficulty with these judgments. The subject saw each comparison name lateralized once to the left and once to the right, resulting in a total of 38 trials.

Procedure

The subject sat approximately 1 m from a CRT screen, with two buttons before him. One button was labled "goat" and the other was "other". The subject was told that he soon would see the names of animals. When he saw a name, he was to press the "goat" button if a goat was larger than that animal, and the "other" button if the named animal was larger than a goat. Before each

trial he fixated on a dot in the center of the screen. The stimulus word was presented 1.5 degrees to the left or the right of the dot. Stimuli were presented in a random order, each word was presented once in each visual field, but the order of the field of presentation was varied randomly. The subject always responded using his left hand.

Results

First, and most basic, both hemispheres could perform this task. Only one error was committed in the entire experiment (for "moose," which he apparently misread as "mouse"), resulting in 100% accuracy in all but the right hemisphere "large" condition, which had 89% accuracy. Not surprisingly, there were no significant differences in the comparisons of error rates, $p > .25$ in all cases.

Next, we examined the response times. Again, there was no difference between the hemispheres (1.203 vs. 1.264 sec for the left and right, respectively), $F < 1$. Nor was there an effect of the size of the objects, $F(1, 17) = 1.65$, $p > .20$. However, the pattern of times was different for the two sizes for each hemisphere, as witnessed by a significant interaction between size and hemisphere, $F(1, 17) = 5.69$, $p < .03$. For the small animals times were 1.178 and 1.482 sec whereas for the large ones times were 1.227 and 1.047 sec for the left and right hemispheres, respectively. This result is a puzzle, but is very fortunate in a way: It demonstrates that our failure to find effects of hemisphere are not simply a reflection of noisy data or insensitive statistical procedures.

We were concerned that perhaps some of the comparison objects were too disparate in size, allowing the judgment to be made without imagery. Thus, we

examined only the 5 objects just larger than a goat and the 5 just smaller than a goat. All of these items were evaluated correctly in both hemispheres. The response times were 1.318 sec and 1.319 sec for the left and right hemispheres, respectively, $F < 1$. No other effect or interaction approached significance in this analysis, $p > .14$ in all cases.

In short, then, these data provide evidence that both hemispheres can form images of general shapes, as is required to evaluate the relative sizes of similar-sized objects.

Task 2

In the previous task, both hemispheres were essentially perfect; this ceiling effect prevents us from discovering whether one hemisphere is *in fact* better at generating images of shapes. This task was intended to be more difficult, which should prevent a ceiling effect and allow a meaningful comparison of the hemispheres' performance.

Method

Materials

Twelve common objects were selected that are higher than they are wide: nose, book, ape, ear, mug, boot, jar, coat, chair, barrel, pear, and vase; an additional twelve were selected that are wider than they are high: flag, cake, eye, bike, buckle, dollar, sofa, bow, sofa, crate, tomato, and bowl. In addition, a professional artist drew a connonical black-and-white line drawing of each object, and these drawings were photographed and made into slides. Finally, the names of the objects were typed in a random order on a sheet of paper.

Procedure

The subject again sat before the CRT, fixated on the dot, and viewed

lateralized stimuli. Now, however, there were three experimental conditions: The <u>names condition</u> consisted of his seeing the names of the objects, presented in a random order, with each word being presented once in each field with the order of the field of presentation also being randomized. One button was labeled "higher;" the other "wider." He pressed the appropriate button if the named object was higher than it is wide or wider than it is high.

The <u>pictures condition</u> consisted of his seeing the slides of the objects, presented in a random order with the field of presentation also being randomized. He made the same judgment as in the names condition, but now on the basis of what he saw. This condition was included to provide a baseline for perceptual performance of the task.

Finally, the <u>picture-name association</u> task consisted of his seeing the pictures as in the previous condition, but now he simply pointed to the appropriate name on the sheet in front of him. This task was included as a baseline against which to compare performance in the imagery task (the "names task"); if he cannot read certain names, he clearly will not be able to image and evaluate the corresponding objects.

The subject was tested in the names task first, then the picture task, then the picture-name association task. This order ensured that he could not be memorizing the responses to the actual pictures and using them in the names task. The subject had approximately ten minutes rest between tasks.

<u>Results</u>

<u>The names task</u>. There was no significant difference in the accuracy of the two hemispheres in performing this task (70.8 versus 66.7% for left and right, respectively), $F < 1$. Nor was there an effect of response

category, $F < 1$ (66.7 versus 70.8 for taller and wider, respectively). However, there was a marginal trend for the left hemisphere to be more accurate with the wider stimuli (79.2 versus 62.5%) whereas the right was more accurate with the taller stimuli (70.8 versus 62.5%), $F(1, 22) = 3.19$, $p < .09$. This marginal trend reflected a more complicated interaction between hemisphere, response category, and block, $F(1, 22) = 6.82$, $p < .02$. The interaction between hemisphere and response category was dramatic for the first block (33.3 versus 83.3% for taller and wider for the left hemisphere, and 83.3 versus 50% for taller and wider for the right) whereas the interaction was diluted by the second block. There were no other significant effects or interactions in this analysis, $p > .14$ in all cases.

A closer examination of the data revealed that almost half of the errors were committed in the first ten trials. This was not surprising, given that the task was novel and the subject had had only a few practice trials. Thus, it was of interest to examine the data excluding the first 10 trials. Now the left hemisphere was accurate 81% versus 70% for the right, $t(19) =$??, $p > .1$.

The same story emerges when we examine the response times: There was no systematic effect of hemisphere (2.266 versus 2.318 sec for left and right), $F < 1$, nor were there any interactions involving hemisphere, $F < 1$ in all cases. In fact, the only significant effect reflected faster times on the second block (2.908 versus 1.675 sec), $F(1, 22) = 36.18$, $p < .001$. All other effects and interactions, $p < .19$.

When we excluded the first 10 trials, the two hemispheres took virtually the identical amount of time to make the judgments, 2.018 vs. 2.013

sec for the left and right, respectively, $t < 1$.

The pictures task. The two hemispheres again both could perform the task, 85 and 91.7% accuracy for the left and right, respectively, $F < 1$. Similarly, there was no difference in accuracy for the different response categories (91.7 versus 85.4 for taller and wider, respectively), $F(1, 22) = 1.48$, $P > .23$. In fact, there were no significant comparisons in these data, $p > .13$ in all cases.

The analysis of the response times revealed that responses were faster on the second block (2.229 versus 1.501 sec), $F(1, 22) = 8.59$, $p < .01$. Although the right hemisphere appeared slighly better at this perceptual discrimination task (1.971 versus 1.759 sec for left and right, respectively), this difference was not significant, $F < 1$. No other comparisons were significant, $p > .4$ in all cases.

We also performed analyses that included data from both the names task and the pictures task, looking to see if the hemispheres differed in their imagery ability relative to the perceptual baseline. First, there was no difference in the accuracy of the two hemispheres, $F < 1$, nor in the relative accuracies of the hemispheres in the two tasks, $F(1, 22) = 1.23$, $p > .25$. However, the relative accuracy of the hemispheres differed for the different stimulus types in the different tasks, $F(1, 22) = 4.00$, $p < .06$. The interaction between response category and hemisphere noted above only occurred in the names task. In addition, there was a marginal interaction between task, block, hemisphere, and response, which again reflected the interaction noted above, $F(1, 22) = 3.21$, $p < .09$. Furthermore, the pictures task was in general easier than the names one, $F(1, 22) = 14.44$, $p < .001$. No other interaction

involving task was significant, $p > .15$ in all cases.

The analysis of response times from both tasks was consistent with the foregoing analysis: Not only was there no difference in times for the two hemispheres, $F < 1$, but the relative accuracies were the same in both tasks, $F < 1$. There also was an interaction between task and block, with greater improvement in the imagery task, $F(1, 22) = 4.04$, $p < .06$. In fact, by the second block of trials the overall times were very similar (1.675 and 1.501 sec for imagery and perception, versus 2.908 and 2.229 for the two tasks on the first block). No other interaction involving task was significant, $p > .14$ in all cases.

The picture-name association task. Finally, the left hemisphere performed with 100% accuracy in the picture-name association task, and the right hemisphere performed with 92% accuracy. Thus, the 11% difference we found in the names task, although not significant, is about what could have occurred due to factors having nothing to do with imagery.

Discussion

The left and right hemisphere clearly could perform two imagery tasks that do not involve generating multi-part images. Only a "skeletal image" (a general outline) is necessary to decide if one object is larger than another or to determine the height/width shape envelope of a single object. Thus, we have reason to believe that the PICTURE processing module operates effectively in both hemispheres. This inference makes sense if this module essentially activates the representation of visual information, which is stored in a "cell assembly" (Hebb, 1966) or the like. Given that both hemispheres can store visual memories, there is no compelling reason why these memories should not be

able to be activated to reinstate a visual image of the stored object or part. In addition, in order to "inspect" the images to perform the task the FIND module had to be effective, and thus these results support the previous ones indicating that JW's imagery problem cannot be identified with a faulty FIND module.

The next question, then, is whether both hemispheres can perform as well when images of non-linguistic stimuli must be formed from separate parts.

Experiment 8

The materials and task used in the foregoing experiments were considerably different than those used in the experiments with letters of the alphabet. Perhaps we have a found a deficit for letters per se, and not for multi-part images. To rule out this possiblity, in this experiment we used materials used in the previous experiment to demonstrate an image generation deficit when parts had to be arranged correctly in the image in order to perform a task. In this experiment we asked our subject whether an animal's ears protrude above the top of its skull or whether they flop down along the side of its skull. Which is the case for a beagle? a mouse? a wolf? Earlier experiments indicated that people use imagery in making just this sort of judgment (see Kosslyn & Jolicoeur, 1980, 1984), and fortunately our subject's interest in animals had led him to have ample exposure to these sorts of stimuli. In addition, because this judgment requires relating two parts--the ears and the skull--we had reason to expect that the right hemisphere would have difficulty. Thus, in this experiment the subject saw animals' names lateralized, and simply judged the relationship between the ears and skull.

Method

Materials

The same stimuli used in the size-comparison experiment were used here. As before, twenty animal names were presented in a random order, with the field of presentation also being randomized; each name was presented once in each field. Ten of the animals had ears that protruded above the skull and 10 had ears that flopped down alongside it.

Procedure

The two keys were now marked with small drawings, one showing a stylized skull with an ear sticking up (a small triangle above a semicircle) and the other showing a stylized skull with an ear hanging down (a "U" hanging within a semicircle). The patient was told that he would see the names of animals and would be asked to judge whether each animal's ears protruded above the top of the head or hung down. Drawings were shown and the subject correctly classified the drawings. He was told which key to press for each judgment, and again fixated on the dot before each trial. Two blocks of trials were administered.

Results

The most striking aspect of the results is the relative accuracies of the two hemispheres: 87.5% vs. 45% for the left and right hemispheres, respectively, $F(1, 18) = 18.45$, $p < .001$. In addition, upright ears were judged more accurately than floppy ears (90% vs. 52.5%), $F(1, 18) = 5.89$, $p < .03$, but this may simply reflect a response bias. And the effects of type of stimulus were different for the two hemisperes (85 and 90% for upright and floppy in the left, and 75 and 15% for upright and floppy in the right), $F(1, 18) = 10.79$, $p < .005$. No other effects or interactions were significant, $p >$

.2 in all cases.

The analysis of response times revealed improvement with block, $F(1, 18) = 55.6$, $p < .001$ (2.923 vs. 1.530 sec for the first and second block, respectively). There was no effect of hemisphere (2.139 and 2.315 sec for the left and right, respectively), $F < 1$, nor of any other effect or interaction, $p > .2$ in all cases.

Discussion

The results from this task are in stark contrast to those from the two previous ones, and are quite similar to those from the lower case cue imagery task. Unlike the case for letters, however, one could argue that the right hemisphere was simply unfamiliar with the shape of ears. However, given the hemispheres' comparable knowledge of subtle size differences among animals, and the left hemisphere's knowledge of ears, there is no clear reason why the right hemisphere should have a selective deficit for knowledge about ears.

In order to perform the ears-judgment task, the subject must coordinate an image of the ears with an image of the head, which we claim requires the PUT processing module to access and use a stored description of the relation. Thus, the failure of the right hemisphere to perform this task converges nicely with our earlier results in a very different task. Furthermore, the results of the experiments reported so far in this paper converge in demonstrating that the FIND, PICTURE, LOAD, and REGENERATE processing modules operate effectively in both hemispheres. These data taken as a whole are consistent with our claim that the PUT module is a distinct entity, and JW's right hemisphere has a deficit in using this module to generate multi-part images.

Experiment 9

Have we really identified a deficit in a particular processing module, or something more general? In this last set of experiments with JW we show that we have discovered something more specific than a deficit in memory for details or in serial processing. We do so by showing that an alternative retrieval strategy can allow JW to perform the task. Specifically, neuropsychological data on the apraxias and the visual agnosias imply that motor and visual memories can be separately spared or destroyed after brain damage, and the existence of alexia (inability to read) without agraphia (inability to write) and vice versa makes this point especially strongly for letters (see Geschwind, 1965). We have shown that JW can recognize letters, and so he must have their representations stored in long-term memory; in addition, JW is an excellent artist, able to produce highly-realistic drawings of cars and other objects from memory. Thus, we attempted to lead JW to perform the task by asking him to draw the letters. If he can perform the task using a drawing strategy, but not an imagery one, we can argue that his deficit is not in memory for details, serial processing, or in a processing module used to perform both activities.

Method

This experiment was conducted about three months after the previous one. Thus, we began by replicating our original findings, using the second set of letters (from Experiment 3). After this, we administered training trials, and then looked for transfer to the third set of letters.

Materials

The materials were the same as those used in Experiments 3 and 5.

Procedure

The experiment had three phases: The first phase was a simple replication of our original findings. The procedure here was identical to that used in Experiment 1. One block of 40 trials was administered. The second phase had multiple components, described below, which were used to train JW to form images by "mentally drawing" the letters. The final phase was identical to that of Experiment 5, where we simply switched him to the new set of letters. The details of each procedure will be described as they become relevant.

Results

Lower case cue task.

As is evident in Figure 5, the results from the basic imagery task replicated our previous findings; indeed, the right hemisphere performed more poorly than we had found before: The left hemisphere was accurate 95% of the time and the right was accurate only 30% of the time, $F(1, 8) = 67.6$, $p < .001$. In addition, there was no improvement with the second block, $F < 1$, or any other effect, $p > .19$. There was no effect of hemisphere in the analysis of the response times (1.316 sec for the left hemisphere compared to 1.342 sec for the right), $F < 1$, and no other effects or interactions were significant, $p > .2$ in all cases.

"Mental drawing" trials.

There were three phases of these trials. We began by simply asking JW to draw the upper case versions of the letters, with his left hand and his eyes closed. He could do this perfectly when the letters were presented to either hemisphere. Clearly, visual and motor representations need not be related in the brain; this finding is consistent with reports of alexia without agraphia

and (vice versa), and visual object agnosia without apraxia (and vice versa). We next asked him to "draw the letters in your head" during the basic lower case cue imagery task. These instructions had no effects whatsoever, as witnessed by the left hemisphere's being accurate 100% of the time and the right hemisphere's being accurate only 20% of the time, $F(1, 8) = 51.2$, $p < .001$. There was no evidence of a response bias or consistent guessing strategy in the right hemisphere, with errors being distributed relatively evenly for the different stimulus types (10% versus 30% accuracy for curved and straight, respectively), $F < 1$. No interactions were significant, $p > .25$. There were no significant differences in the analysis of response times, although there was a marginal trend for the left hemisphere to be faster (2.086 versus 2.830 sec), $F(1, 8) = 3.84$, $p < .09$; no other effect or interaction approached significance in this analysis, $p > .16$ in all cases.

In the final procedure, we asked him to draw the upper case versions of the first three lower case cues shown to the right hemisphere, and then to classify the upper case version as straight/curved. He was successful on these initial trials. After the first three letters we told him to "do the same thing, but without actually drawing the letters; drawn them in your mind." And this proved to be a successful strategy. His hand was prevented from moving (in an attempt to preclude gross cross-cuing) by an experimenter who was not watching the lower case stimuli (and hence could not provide non-verbal cues on how to respond correctly). Three blocks of trials were conducted. As is evident in Figure 5, on these trials, there was no difference in the accuracy of the two hemispheres, $F(1, 8)= 1.0$, $p > .34$. The left hemisphere was perfect by the second block, whereas the right was perfect only on the third block,

resulting in an interaction between hemisphere and blocks, $F(2, 15) = 3.50$, $p < .06$. In addition, the improved accuracy in the right hemisphere with successive blocks lagged for the straight stimuli, whereas the improved accuracy in the left hemisphere was equivalent with both types of stimuli, resulting in significant interaction between hemisphere, block, and stimulus type, $F(2, 16) = 3.50$, $p < .06$. In general, there was improvement blocks, $F(2, 16) = 3.70$, $p < .05$. No other comparisons were significant, $p > .13$ in all cases.

The analysis of response times painted a more complex picture. The most important finding is that although the right hemisphere developed the abilility to perfom the task, it was still slower than the left (6.054 versus 4.351 sec), $F(1, 8) = 19.45$, $p < .005$. In addition, there were interactions between block and replication, $F(2, 16) = 3.65$, $p < .05$, and between hemisphere, block, and replication, $F(2, 16) = 3.34$, $p = .061$. But these interactions reflected a four-way interaction between hemisphere, block, stimulus type and replication, $F(2, 16) = 6.56$, $p < .009$. This interaction is illustrated in Figure 6. As is evident, the data become more systematic with successive blocks; on the first block, different patterns of responses occurred on the different replications for the different types of stimuli, whereas by the third block the data were quite regular. Other than the finding that times generally decreased on the final block, $F(2, 16) = 7.01$, $p < .01$, there were no other significant comparisons, $p > .11$ in all cases.

<u>Transfer trials</u>.

Finally, we simply switched the stimuli to the third set of letters. Two blocks of trials were administered. The results are illustrated in Figure

7. The analysis of accuracy data revealed no significant comparisons, and only the effect of stimulus type was marginal, $F(1, 8) = 3.5$, $p < .1$. In particular, there was no difference between the hemispheres (95 vs. 87.5%), $F < 1$, and $p > .3$ for all other comparisons.

The analysis of the response time data again revealed that the left hemisphere was faster than the right, $F(1, 8) = 11.16$, $p < .01$. In addition, there were faster responses on the second block, $F(1, 8) = 67.04$, $p < .001$, marginally faster responses to curved stimuli (2.817 versus 3.299 sec), $F(1, 8) = 4.07$, $p < .08$, and faster responses on the second replication of a letter (3.454 versus 2.662 sec), $F(1, 8) = 36.6$, $p < .001$. None of the interactions was significant, $p > .14$ in all cases.

To examine the degree of transfer from the first set of letters we analyzed together the data from the final two blocks of the previous condition with the two blocks of transfer trials. The accuracy rates were equivalent in the two conditions in all respects. Not only was there no difference in overall accuracies, $F < 1$, but no interaction was significant with condition, $p > .12$ in all cases. In particular, the difference in accuracies for the two hemispheres was the same in both conditions, $F < 1$ for the appropriate interaction.

The analysis of the response times indicated that times were actually faster with the new items (4.904 versus 3.058 sec), $F(1, 16) = 26.3$, $p < .001$. No other factors interacted with condition, however, $p > .11$ in all cases.

INSERT FIGURES 5, 6, AND 7 HERE

Discussion

These results are in sharp contrast to those found earlier with JW: he now can do the task in his right hemisphere. Clearly, the impairment observed before does not reflect a deficit in memory for the appearance of letters or in serial processing in general. However, he still is taking more time in the right hemisphere, and is in general much slower than he was in the earlier experiments (in which times usually were in the one and two sec range, as opposed to the three or more sec range here). Apparently, we helped JW discover an alternate access route to the stored information about the letters' appearances. But even so, this access route was not equally efficient in the two hemispheres.

Although the success of JW's right hemisphere after motor practice puts to rest any nagging doubt left by the previous visual imagery experiments as to whether or not the goal of the task had been understood by the right hemisphere, it raises a host of new questions: Was imagery of some sort involved here? Did JW acquire an ability to use the PUT processing module to access the stored representations in a new way? Or has an altogether different system of motor imagery been marshalled by the right hemisphere? To what extent are visual and motor imagery separable? That is, it is possible that JW performed this task using not visual, but motoric imagery. The idea of motoric imagery has been discussed at least since Piaget's seminal writings (for an overview see Piaget & Inhelder, 1970). Furthermore, numerous researchers have informally noted that there seems to be a motoric component to mental rotation. For example, Shepard & Metzler (1971) asked people to decide whether two block-like forms had the same shape, irrespective of the orientation of the forms. The decision times increased linearly with increases in the angular disparity in the forms' orientations. Many people report the

introspection of "mentally holding" the forms and "twisting" them into congruence. Such introspections are consistent with Parsons' (1983) demonstrations that the ease of mentally rotating a body part is related to the ease of actually performing that movement.

In the absence of EMG data during our testing sessions, we cannot implicate a purely motor strategy, consisting of movements imperceptible to the experimenters. However, the straight/curved judgment would certainly lend itself to performance by motor feedback, and the greatly increased response times for these trials lend some plausiblity to this speculation. In any event, it is important to note that even if motor imagery and visual imagery may often work together, this does not imply that the systems themselves are integral (i.e., share representations or processes). Indeed, the present results underscore the existence of at least some distinct processing modules used by the two systems. The precise mechanisms of coordination of visual and motoric image generation are by no means clear, but certainly seem worthy of further investigation.

III. EXPERIMENTS WITH VP

We tested a second subject, VP, in our tasks with an eye toward discovering whether a different pattern of deficits would emerge. We originally decided to test split brain patients in these tasks because we suspected that the PUT processing module used some of the same computational machinery used in other sorts of symbol-manipulation tasks, and we knew something about the general deficits of JW's right hemisphere. Our second subject, VP, has considerably more reasoning and linguistic ability in her right hemisphere, which led us to examine whether she could use the PUT module

to form multi-part images. Thus, another avenue for evaluating the theory is to compare the deficits in VP's processing with those in JW's processing, looking for a single underlying pattern cutting across different deficits. In addition, by comparing subtle differences in the nature of the functional dissociations in the two subjects we hoped to learn something about the mechanisms used by the processing modules.

Subject

VP is a 32 year old right handed female. At age n[illegible], following febrile illnesses (including measles and scarlet fever), she began having recurrent seizures. The initial seizures were infrequent and were controlled by anticonvulsant drugs until after she graduated from high school. By 1976 she was experiencing episodes of blank staring several times a day that would last for seconds. EEG indicated bilateral 4 cps spike and slow wave activity, and sharp activity with left temporal predominance. In 1979 she was being administered multiple anticonvulsant drugs, which failed to control generalized, major motor seizures, absence, and myoclonic seizures. She was referred to Dr. M. Rayport at the Medical College of Ohio. In early April 1979 she underwent partial anterior callosal section, and the resection was completed in a second operation seven weeks later.

A neurological exam following the operation revealed no evidence of focal activity, and her IQ scores were in the normal range. When we tested her she was alert and thoughtful, carrying on normal conversation and fully oriented. VP could comprehend language in her right hemisphere immediately after surgery. Within one year she was actually able to produce speech from her right hemisphere (see Gazzaniga et al, 1983, for additional details).

Experiment 10

We started our investigation of VP's imagery abilities with the same basic lower case cue "straight/curved" imagery task and the same perceptual analogue control task used in Experiments 1 and 2.

Method

Materials

The lower case cue task used the same materials used in Experiment 3, whereas the upper case control used the upper case versions of these letters.

Procedure

The procedure used in Experiment 1 was also used here. However, four blocks of trials of the lower case cue task were used initially.

Immediately following the four blocks of imagery trials two blocks of the upper case controls were administered, using the procedure of Experiment 2. The upper case versions of the letters used in the previous task were shown in the same random order used previously.

Finally, following the upper case controls were two more blocks of imagery trials with the lower case stimuli.

Results

Initial imagery trials.

The results are presented in Figure 8. The analysis of the accuracy data revealed that there was improvement with successive blocks, $F(3, 24) = 4.0$, $p < .03$, and better performance in the left hemisphere (95% versus 67.5%), $F(1, 8) = 6.45$, $p < .04$. No other effects or interactions were significant, $p > .4$ in all cases.

The analysis of the response times revealed an interesting, unexpected

effect: Although there was no effect of hemisphere in general, $F(1, 8) = 2.17$, $p > .17$, there was an effect of hemisphere for the first replication: For replication 1 (i.e, the first time a letter was presented in a block), the left and right hemispheres required 3.759 sec and 5.561 sec, respectively, $F(1, 8) = 14.93$, $p < .01$; for replication 2, the left and right hemispheres required 4.573 sec and 4.305 sec, $F < 1$. This pattern of means produced an interaction between replication and hemisphere, $F(1, 8) = 11.01$, $p < .02$. There was also an effect of block, as is evident in Figure 8, $F(3, 24) = 8.97$, $p < .001$, and a marginally significant tendency for faster times for judgments of straight stimuli (6.275 sec vs. 4.467 sec for curved and straight, respectively), $F(1, 8) = 4.11$, $p < .08$. There was also a hint of a trend for increasingly faster times on the first replication of each successive block (7.147, 6.652, 4.876, and 3.642 sec) compared to little speeding up on the second replication after the first block (7.097, 4.314, 4.983, 4.257 sec), $F(3, 24) = 2.13$, $p = .12$, for the interaction between replication and block. Finally, there was no overall effect of replication, $F < 1$, nor of any other interaction, $p > .25$ in all cases.

INSERT FIGURE 8 AND 9 HERE

Perceptual control.

There were no significant differences in the accuracy data, $p > .3$ in all cases. In particular, the two hemispheres were very accurate, 100% and 97.5% for the left and right, respectively, $F = 1.0$.

The response times revealed improvement with the second block (3.369

versus 1.990 sec), $F(1, 8) = 10.99$, $< .01$, and a trend for a smaller effect of block in the left hemisphere, $F(1, 8) = 3.73$, $p < .09$. There was no systematic difference in the speed of responding from the two hemispheres (2.409 versus 2.950 for the left and right, respectively), $F < 1$. No other effects or interactions were significant, $p > .1$ in all cases.

Final two imagery blocks

As is evident in Figure 9, VP's performance on these two blocks was very different from her performance earlier. Accuracy improved dramatically in the right hemisphere (87.5%, compared to 100% for the left), but the difference between the hemispheres was still marginally significant, $F(1, 8) = 4.55$, $p < .08$. No other effect or interaction was significant in this analysis, $p > .3$ in all cases. By the second block, however, there was no effect of hemisphere (95 vs. 100% for the right and left, respectively), $F < 1$.

The response times revealed a similar pattern: There was no effect of hemisphere, $F < 1$, block, $F(1, 8) = 1.77$, $p > .2$, or any other effect or interaction, $p > .25$ in all cases.

Discussion

As was found with JW, VP's right hemisphere initially had great difficulty in performing the imagery task. However, there was a clear initial difference between the pattern of response times found with VP and that found with JW: Unlike JW, VP's right hemisphere's response times were slower in the right hemisphere only on the first replication within a block. This practice effect seemed quite transient, however, occurring on each block, although there seemed to be a tendency for the effect to accumulate gradually. We will consider the implications of these data in more detail after discussing the

results of the following experiments.

The perceptual controls were a different story: Both of VP's hemispheres clearly understood the basic task, and could evaluate the upper case letters when they were actually presented.

Finally, after the perceptual control VP clearly was able to perform the basic imagery task in both hemispheres. These results are in sharp contrast to JW. We next asked whether this was indeed because she could generate images of the letters or somehow learned the correct responses (even though no feedback had been given).

Experiment 11

In this experiment we used a different task: We now asked VP to decide whether there is a vertical line at the far left of the upper case letter. If she merely learned the responses to the letters, she should perform at close to chance in this task. On the other hand, if she learned to generate images of the letters, there should be considerable transfer even though the new task requires a different judgment--and this judgment conflicts in most cases with the responses made in the straight/curved task.

Testing VP on this new task is particularly important here because in Experiment 12 we will look for transfer of a different kind, and argue that failure to transfer implicates a specific type of computational mechanism; thus, it is important to demonstrate that she does not have difficulty in transfering to a new task per se.

Method

Materials

The same letters used in the previous experiment were used here. Recall

that three of the straight letters (M, H, and E) and two of the curved letters (B and D) had straight lines on the left; the other five letters did not have a vertical line on the left. The same order of presentation used in the previous experiment was used here.

Procedure

The procedure was the same as in the previous experiment, except that the subject was now instructed in the new task: Instead of indicating whether the upper case letter was composed of only straight lines or some curved lines, she was now to indicate whether or not there was a vertical line on the far left. Examples were given using non-stimulus letters until her left hemisphere, at least, clearly understood the task. Two blocks of trials were given.

After the imagery task, we conducted a perceptual control task like that used before (Experiment 2). We again showed the upper case letters themselves. Now, however, we asked the subject to make the vertical-line judgment, not the straight/curved one used before. Again, two blocks of trials were administered. This control task was conducted after the imagery trials to obtain a baseline; this ordering of the tasks prevents her from memorizing the responses during the control and using this information to perform the imagery tasks.

Results

The results from the imagery task and the perceptual control task are presented in Figure 10.

Imagery task.

As usual, accuracy was superior in the left hemisphere, $F(1, 8) = 9.52$,

$p < .03$, and there was a trend toward improved performance with successive blocks, $F(1, 8) = 4.24$, $p < .08$. However, by the second block performance was markedly improved in the right hemisphere (80% vs. 95% for the right and left, respectively), $F(1, 8) = 2.57$, $p > .1$.

There was only one significant difference in the comparisons of response times, due to blocks, $F(1, 8) = 12.72$, $p < .01$. Notably, there was no effect of hemisphere, $F < 1$, stimulus type, $F(1, 8) = 1.41$, $p > .25$, or replication, $F < 1$. Nor were any interactions significant, $p > .18$ in all cases.

The fact that there was some savings in this task over the initial one was revealed in analyses that included the first two straight/curved imagery blocks and these two blocks. Whereas the original blocks required a mean of 6.302 sec, these required only 4.300 sec, $F(1, 16) = 8.62$, $p < .01$. In addition, whereas there was a difference in the left vs. right hemisphere in the original task, 5.444 vs. 7.161 sec, $F(1, 8) = 4.78$, $p = .06$, there was no difference here, 4.238 vs. 4.362 sec., $F < 1$ (this interaction was not significant in our analysis, however; $F(1, 16) = 2.16$, $p > .15$). The only other effect of interest here was an interaction between hemisphere and replication, $F(1, 16) = 8.70$, $p < .01$, revealing the now-familiar effect of practice in the right hemisphere.

<u>Perceptual control</u>.

There were no significant effects in the analysis of accuracy rates. However, there was a trend for improved performance on the second block, $F(1, 8) = 3.6$, $p < .1$, and there was a tendency for an interaction between block and hemisphere, $F(1, 8) = 3.6$, $p < .1$; this interaction reflected slightly superior

performance in the right hemisphere on block 1 (90 vs. 95% for the left and right hemisphere, respectively) compared to slighly inferior performance in the right hemisphere on block 2 (90% vs. 80%).

There were no differences in response times for the different blocks or hemispheres, $F < 1$ in both cases. However, responses to vertical-line-on-left stimuli were faster than the others (2.116 vs. 3.583 sec), $F(1, 8) = 5.52$, $p < .05$, and there was an interaction between hemisphere and replication, $F(1, 8) = 5.12$, $p = .054$. This interaction documented an increase in time over replications for the left hemisphere (2.413 and 3.062 sec for replication 1 and 2, respectively) but a decrease in time over replications for the right hemisphere (3.877 and 2.045 sec for replication 1 and 2, respectively). There was a marginal trend for faster times on the second replication in general, $F(1, 8) = 3.65$, $p < .1$. No other interaction was significant, $p > .25$ in all cases.

Another way to assess the performance of the right hemisphere in the imagery task is by comparison to performance in the perceptual baseline task. Thus, we included both sets of data in a single analysis. In general, there was no difference in the accuracy of the two hemispheres, $F(1, 16) = 2.75$, $p > .1$, and their relative performance was equivalent in the two tasks, $F(1,16) = 1.84$, $p > .19$. And in fact, in the analysis of the accuracy data there were only two significant comparisons that involved effects of task: Performance improved more sharply with successive blocks in the imagery condition, $F(1, 16) = 7.36$, $p < .02$, and judgments of vertical-line-on-left stimuli were relatively more accurate than the others in the perceptual condition, but vice versa in the imagery condition, $F(1, 16) = 5.45$, $p < .04$. For all other comparisons

involving task, $p > .1$.

The analysis of response times indicated that times were generally faster in the perceptual task, $F(1, 16) = 7.77$, $p < .02$, and that times tended to decrease more sharply on the second block in the imagery condition, $F(1, 16) = 4.28$, $p < .06$. As before, there was no difference between the hemispheres, $F < 1$, and the hemispheres performed equivalently in the two tasks, $F < 1$. For all other comparisons involving task, $p > .12$.

INSERT FIGURE 10 HERE

Discussion

The results from this experiment give us good reason to believe that VP could form images of the letters. By the second block of trials her right hemisphere was performing the new task about as well as she performed the original task on the sixth block. In addition, there was clear savings in the overall time. Furthermore, performance in the imagery task did not differ for the two hemispheres relative to performance in the perceptual control task. These findings are especially impressive because the responses required here conflict with those required for the straight/curved task, and thus there is the possiblity of proactive interference.

Experiment 12

The results of the previous two experiments demonstrate that VP's right hemisphere can generate images of letters with practice--but practice is definitely required. The pattern of practice effects was unexpected, appearing on the first replication in a block and gradually resulting in the

ability to form images of the letters. This sort of effect may indicate that one or more of the processing modules simply took time to "warm up". If so, then once the modules are all operating VP should be able to transfer to a new set of letters in her right hemisphere. In this experiment we asked her to perform the basic lower case cue task with a new set of letters.

Method

Materials

The final ("transfer") set of letters used in Experiment 5 was also used here.

Procedure

The procedure was identical to that used in Experiment 1. Three blocks of trials were administered.

Results

As is illustrated in Figure 11, the left hemisphere again was more accurate than the right (83.3% vs. 63.3%), $F(1, 8) = 4.8$, $p < .06$, and responses to curved stimuli were more accurate than to straight stimuli (86.7% vs. 60%), $F(1, 8) = 10.24$, $p < .02$, suggesting that there was a slight response bias. In addition, the effects of stimulus type were different over successive blocks (with no change for curved, but steady improvement for straight), $F(1, 16) = 3.38$, $p < .06$, and the effects of stimulus type were different in the two hemispheres (83.3% and 90% for curved letters compared to 83.3% and 36.7% for straight letters in the left and right hemispheres, respectively), $F(1, 8) = 8.53$, $p < .02$. No other effects or interactions was significant, $p > .2$ in all cases.

INSERT FIGURE 11 HERE

The only effect in the response time results that approached significance was due to hemisphere, $F(1, 8) = 4.16$, $p < .08$, with the left hemisphere being faster (4.409 vs. 5.812 sec). No other effect or interaction was significant, $p > .18$ in all cases.

In order to examine possible transfer more carefully, we performed analyses including these data and those from the original three blocks of trials. The analysis of the accuracy data revealed that not only was there no overall savings from the initial to the transfer trials (79.2 versus 73.3% for the initial and transfer trials, respectively), $F < 1$, but there was no difference in the accuracy of the two hemispheres in the two conditions, $F < 1$. In fact, no interactions with condition were significant, $p > .2$, indicating that the initial trials had no effects at all (salutory or otherwise) on the later performance.

The analysis of all of the response times revealed the same pattern. Probably the most telling results were the lack of even a hint of a difference in the relative performance of the two hemispheres in the two conditions, $F < 1$, and the failure to find any savings in overall times (5.845 vs. 5.110 sec for the original and new trials, respectively), $F(1, 16) = 1.38$, $p > .25$. However, there was an interaction between experiments and blocks, $F(2, 32) = 6.80$, $p < .01$. This interaction was due to especially slow times on the very first block in the first experiment (7.123, 5.483, and 4.930 sec for the three blocks) and relatively fast times on the first block in the new experiment (4.329, 5.730, and 5.272 sec for the three blocks). The slow times for the

first set of trials ever received are not surprising, and the relatively high error rates for the first block in the new experiment suggest that she was not expecting new letters and was not carefully considering her decisions before responding.

Two other interactions with condition proved significant in the analysis of the old and new data: The condition by stimulus type interaction reflected her being faster for curved judgments originally but faster for straight judgments in the new data, $F(1, 16) = 5.08$, $p < .05$. The three-way interaction between condition, hemisphere, and replication, $F(1, 16) = 7.70$, $p < .02$, reflected the fact that in the new data times increased slightly for both hemispheres from replication 1 to replication 2 (.189 sec for the left, .333 sec for the right), whereas in the original data they increased for the left hemisphere (.970 sec) while they decreased dramatically for the right hemisphere (2.491 sec); this finding probably reflects a speed-accuracy tradeoff in the first experiment, as noted earlier, and hence is of little interest here.

Discussion

There was virtually no transfer of VP's ability to generate images of the previous set of letters to the new set. VP became able to form images of the first set of letters only with practice. However, the practice apparently was representation-specific: it did not generalize to images of other letters. Thus, she apparently did not become better at using the processing modules in general.

These unexpected findings are particularly interesting because they may allow us to distinguish between two different sorts of mechanisms that might

underlie the operation of the processing modules: On the one hand, the modules could be carried out as they are in the Kosslyn & Shwartz computer simulation, with each module corresponding to a subroutine. On the other hand, the modules could be like those proposed by theorists formulating "massively parallel" neural network models of mental processing (see Hinton & Anderson, 1981). In this case the modules may not correspond to distinct subroutines; rather, they may correspond to specific ways of activating a network. Consider the difference between a written word disappearing because it is erased and one disappearing because it is written in invisible ink that is fading: The first case is like the Kosslyn & Shwartz theory, where data are stored passively and operated on by a separate routine (analogous to an eraser working over a word). The invisible ink example is like a parallel network, where the data themselves are activated (like the ink but in reverse--with the representation itself becoming more activated). In this case, practice at activating one network (representing a particular letter or part thereof) in a specific way (corresponding to operating on data using different subroutines) would not be expected to transfer to other networks (for more details on this sort of theory see Kosslyn, in press).

The fact that the data seem more consistent with a parallel network mechanism is of interest because theories of such networks have been explicitly formulated as models of neural activity. The nature of the mechanisms underlying the processing modules is clearly a topic that warrants further investigation.

IV. GENERAL DISCUSSION

For JW, we found dissociations between the right hemisphere's ability

to perform imagery tasks that require integration of parts during imagery generation versus tasks that require imagery but that do not require integration of parts. This pattern of results is as expected if the FIND and PICTURE processing modules can operate effectively in both hemispheres, but the PUT processing module has selective difficulty in operating in the right hemisphere. We also found a dissociation between the PUT module and the LOAD and REGENERATE modules, which form an image from immediate visual input and maintain that image, respectively. In addition, we showed that the deficit was not due to some more general problem in remembering visual details or engaging in sequential processing. Imagery seems to involve at least one processing module that is not used in language, perception, or drawing.

When we leave the relatively abstract level of description of "processing modules," and turn to the specifics of the mechanisms that underlie the modules, the results from VP are intriguing: They do not fit in neatly with the Kosslyn & Shwartz theory. The modules may not correspond to separate subroutines that operate on passively stored data. Rather, the theory of processing modules may be best regarded as a theory of the types of states neural networks take during image generation.

In conclusion, two general points have been driven home by the results of the experiments reported in this paper. First, imagery is not a simple event, and it does not take place entirely within a single part of the brain. Attempts to localize the "imagery system," as an undifferentiated whole, to one neural locus have not been successful (see Ehrlichman & Barrett, 1982). More recent attempts to bring order to the effects of brain damage on visual imagery have been more successful by breaking imagery down into component imagery

abilities, such as image generation (see Farah, in press). In this paper we demonstrate the usefulness of a still more fine-grained analysis, taking seriously the notion of "natural computation" (Marr, 1982). Using a theory of imagery that was developed on the basis of behavioral data from normal subjects and computational constraints, we looked for functional dissociations among processing modules posited by the theory. The discovery of such dissociations suggests that the theoretical analysis is in fact a description of how functions that actually occur in the brain.

The second general point made by our results is that neuropsychological data can be useful in testing and developing computational theories. In particular, the modular composition of such theories can easily be tested by looking for evidence of dissociations among the modules in the behavior of subjects who have had brain damage (including brain bisection). In addition, some characteristics of the natural computations underlying our cognitive processes may be more obvious through neuropsychological investigation than through the traditional cognitive methodologies. This observation was brought home in the present paper by the apparent failure of the "subroutine" theory of the mechanisms to explain VP's ability to generate images with practice. Neuropsychological data clearly can do more than simply provide a way of testing computational theories: they can provide the motivation for formulating and developing such theories.

APPENDIX: JUSTIFICATION FOR THE STRAIGHT/CURVED IMAGERY TASK

In this appendix we present evidence that the lower case cue straight/curved task requires imagery to perform. Our demonstration is an extension of Brooks' (1968) experiment, in which he found that imaging and perceiving in the same modality selectively interfere with each other. One of his visual imagery tasks required subjects to decide whether each successive corner of a block letter was at the extreme top or bottom. The key to the experiment was that the subjects responded in different ways. In the verbal response condition, they simply said "yes" or "no" aloud; in another they pointed at a "Y" or "N" on a page, for each successive judgment moving down one row in a column of these letters. Brooks found that more time was taken to make the imagery judgments when one had to look for and point to letters on a response sheet instead of simply saying the responses aloud. These results were in sharp contrast to those from a verbal task. In this task subjects were given a sentence (e.g., "A bird in the hand is worth two in the bush") and asked to classify each word as to whether or not it was a noun. This task required holding an auditory/articulatory image of the sentence in mind while considering each word in turn. Now more time was required when subjects said the responses instead of looking and pointing.

Taken together, Brooks' results show that visual imagery involves some of the same processing mechanisms that are used in visual perception but not in auditory or articulatory processing, and vice versa for the auditory/articulatory imagery involved in holding the sentences in mind. We used a variant of Brooks' task to demonstrate that imagery is used when one makes straight/curved judgments about upper case letters from memory. We

assessed the relative interference between perfomance in the straight/curved task when visual or verbal responses were used. We also assessed the relative difficulty of making the responses in isolation, in order to demonstrate that a visual response mode is not in itself more difficult.

Method

Subjects

Sixteen Johns Hopkins University students or recent graduates participated as paid volunteer subjects.

Materials

A response sheet was constructed as follows: The lower case versions of the letters of the alphabet were listed in a random order going down a column. Four different versions of the sheets were made, each having a different random order of the letters. A column to the left of the letters was labeled "all straights," whereas one to the right was labeled "some curves."

Procedure

The subjects each participated in four tasks. The first two tasks were intended to assess the difficulty of making the responses per se, and the second two were used to assess image/percept interference. The tasks were: 1) the subjects said aloud "all straight/some curves" 13 times in succession; 2) they scanned down a column of 26 letters, putting a check mark to the right of the first letter, to the left of the second, to the right of the third, and so on; 3) they read down a column of 26 lower case letters of the alphabet and classified the upper case versions from memory, saying aloud "all straight" or "some curves," as appropriate; and, 4) they read down the column of lower case letters and put a check to one side or the other, depending on the lines used

in the upper case version; the column to the left of the letters was labeled "all straights" whereas the column to the right was labeled "some curves." A different random order of the letters was used in each condition for a given subject, with each of the four orders being used equally often in each condition over subjects. In all conditions, the experimenter used a stopwatch to record the time between the subject's looking down at the sheet and beginning and the last response. Subjects were told to respond as rapidly as possible in all conditions while keeping errors to a minimum (and in fact, there were only three errors in the entire experiment, in the third task). The order of presentation of the tasks was counterbalanced over subjects.

Results

The results of this experiment are illustrated in Figure 12. First, note that saying the responses in isolation (task 1) actually took more time than making check-mark responses in isolation (task 2; with means of .510 versus .450 sec per item for the two responses). Even so, more time was taken to make the straight/curved judgments with the check mark responses than the spoken responses (with means of .925 and .811 sec. per item). This pattern of results was documented in an analysis of variance by a significant interaction between condition (isolated responses vs. straight/curved judgments) and mode of response, $F(1, 15) = 81.9$, $p < .0001$. In addition, the judgment condition generally required more time than the simple response task, $F(1, 15) = 158$, $p < .0001$, but the two types of response were generally of equivalent difficulty, $F(1, 15) = 2.58$, $p > .1$.

INSERT FIGURE 12 HERE

Discussion

The interference effects observed here are like those found by Brooks when his subjects used a pointing response while performing a visual task. This pattern of results contrasts with those he found when a verbal task was performed. Thus, we have evidence that the straight/curved judgment utilizes some of the same processing mechanisms used in visually-guiding the responses, which is to be expected if visual imagery and visual perception share specialized processing mechanisms--as has been demonstrated in numerous experiments (e.g., for reviews see Finke, 1980; Segal, 1971; Podgorny & Shepard, 1978). Given the earlier results of Brooks and others, then, these results can be taken as evidence that imagery is in fact used in this task.

The second key assumption in our using the straight/curved task is that images of letters are constructed a segment at a time. Demonstrating that this is true turned out to be somewhat involved, and a separate report will provide the details of these experiments (Kosslyn & Provost, submitted). Briefly, we first showed subjects how upper case letters could be formed in a 4 x 5 grid by filling in the appropriate cells. We then presented an "x" mark in two of the cells and asked whether both marks would fall on a given letter if it were in the matrix; on half the trials both x's would have been on the letter, and on half the trials only one would have been on the letter. Independent evidence was gathered that this task requires forming an image of the letter in the matrix. In the actual experiments, subjects saw a lower case cue beneath the grid and 300 msec later saw two x marks within the grid. The time to evaluate the x marks was measured. We were able to show that one component of the

response times is the time required to generate an image of the letter in the grid.

The critical manipulation here was that we systematically varied where the x marks were placed on the letter on the "true" trials. We reasoned that the spine, being the single longest segment, would be the "foundation part" to which all other parts ultimately were connected. If so, then the time to image a segment would increase for segments with increasing numbers of segments between them and the spine--and hence it should take more time before segments located increasing numbers of links from the spine were imaged and evaluated. And in fact more time was taken, all other things being equal, when an x was located on a segment more links removed from the spine. For example, on one trial for the letter "G", one x was on the spine (the vertical line on the left) and the other was on the bottom (immediately connected to the spine); on another trial, one x was on the spine and the other was on the short horizontal segment turning inward at the extreme right (two segments removed from the spine). More time was taken in the second kind of trial than the first. The results from control experiments allowed us to rule out various counter explanations for this result. For example, we showed that it was not due to subjects' generating images of all the segments at the same time, but then taking more time to scan ("mentally trace") greater distances along the outline between the x marks. The best explanation for the results taken as a whole was that images of the segments were generated individually, starting with the spine and working outwards.

In short, we felt justified in using the curved/straight task as an example of an imagery task requiring the construction of a pattern from

individual parts, which--according to our theory--implicates the PUT processing module.

Footnotes

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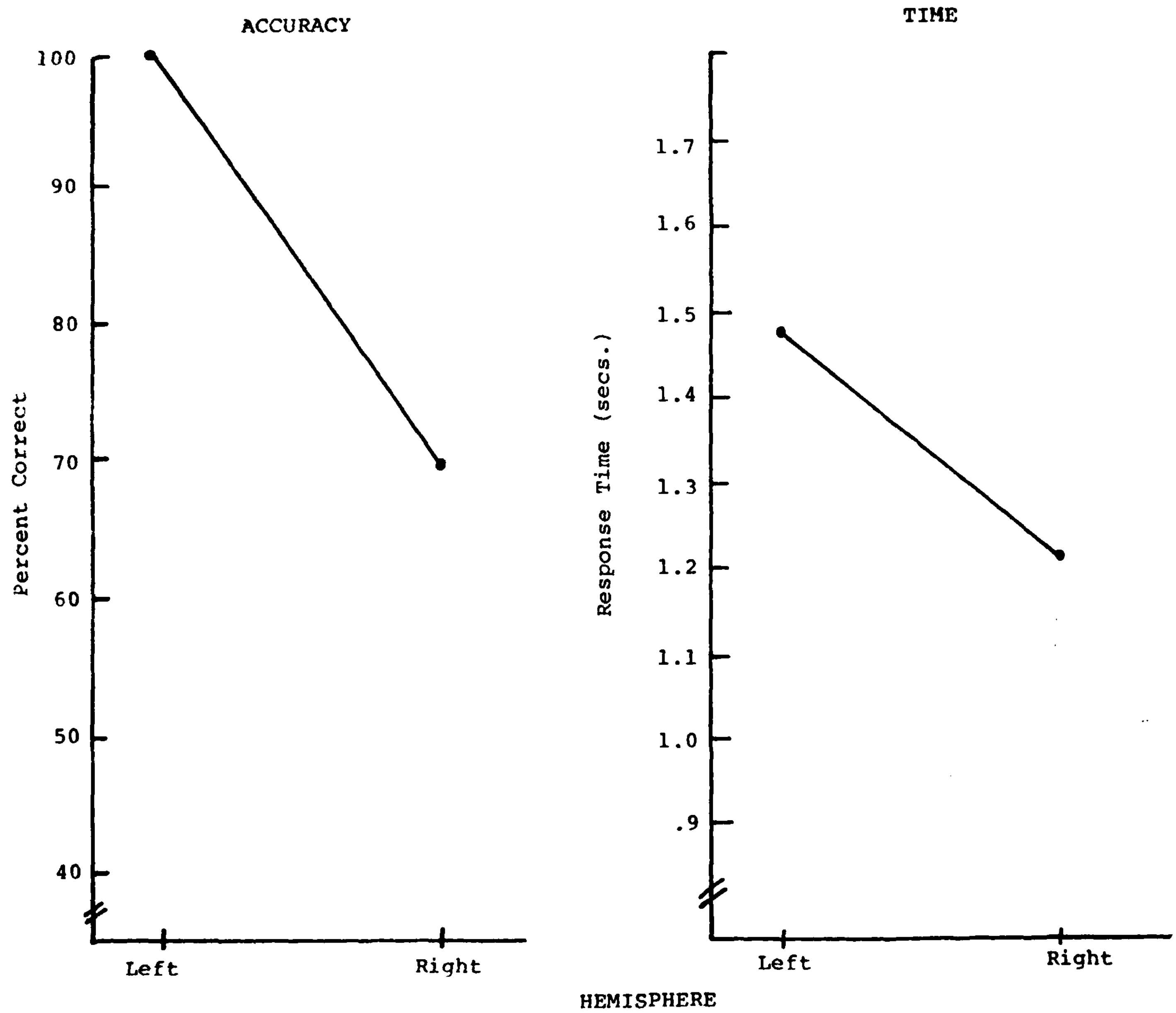
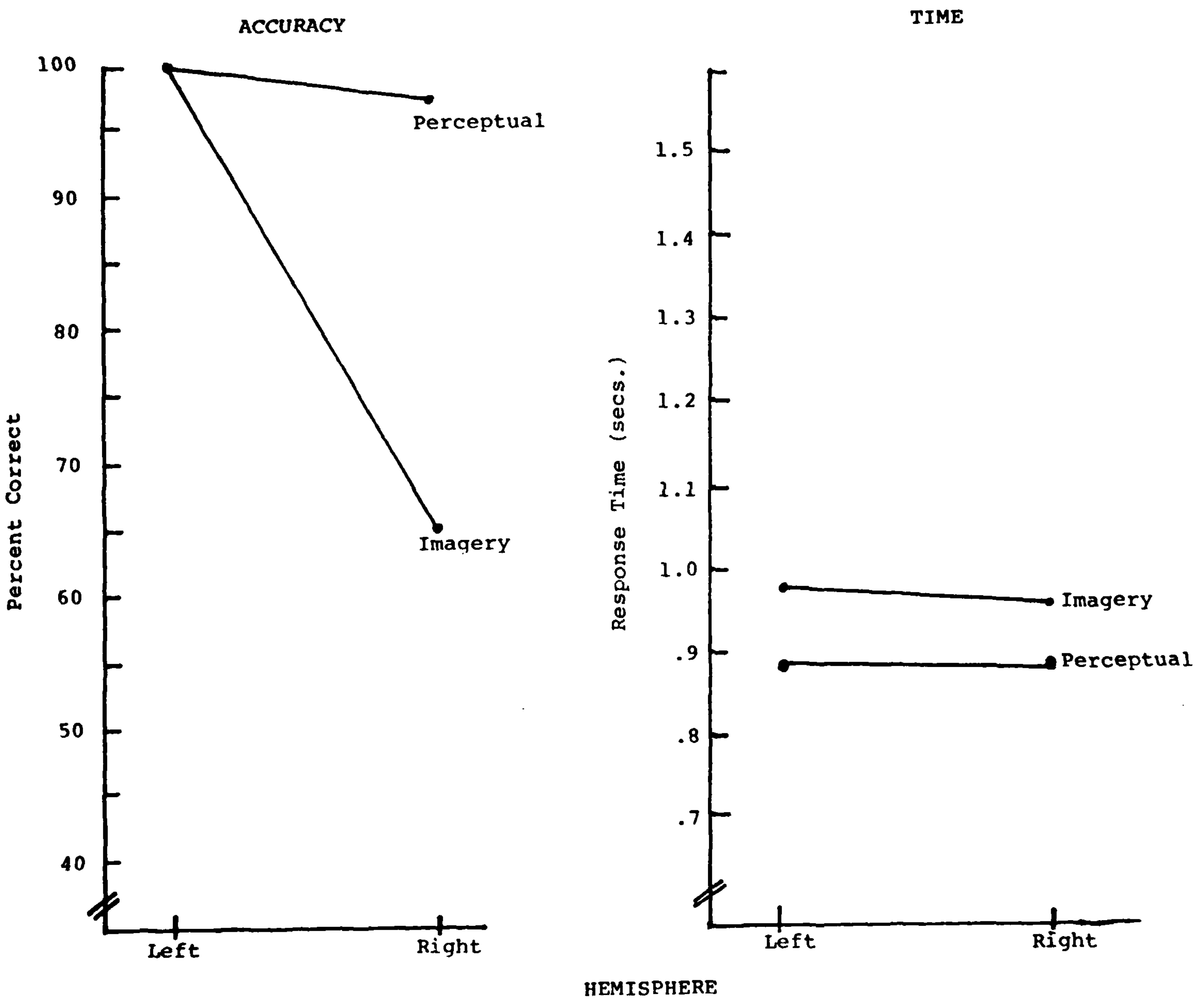
Exp. 1



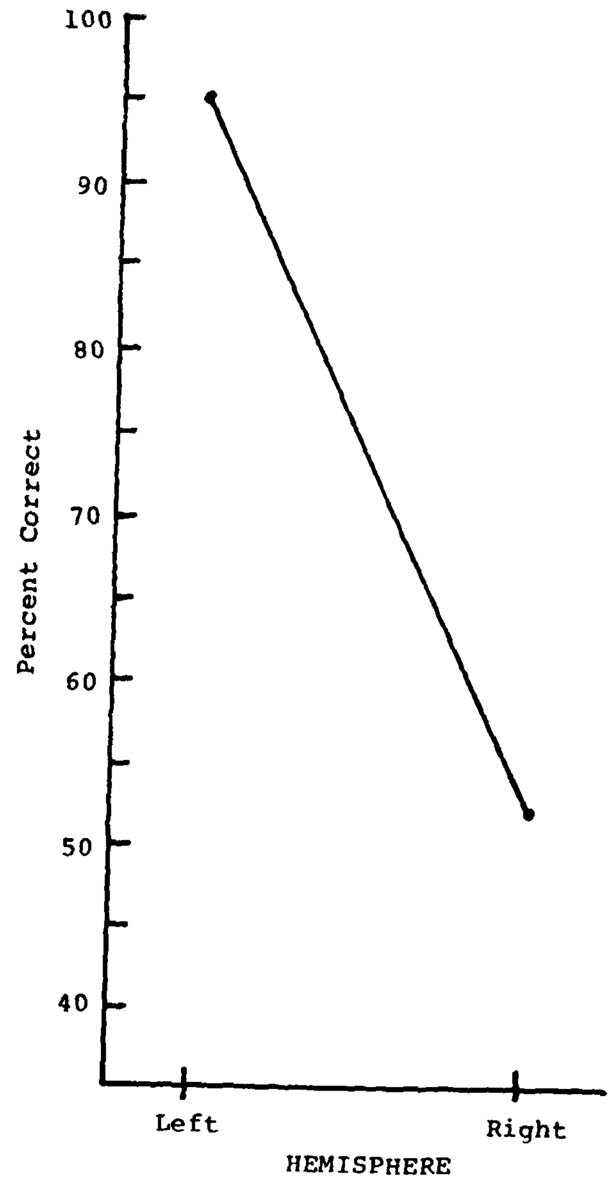
Results of Experiment 1. Basic straight/curved imagery task.

Exp.2



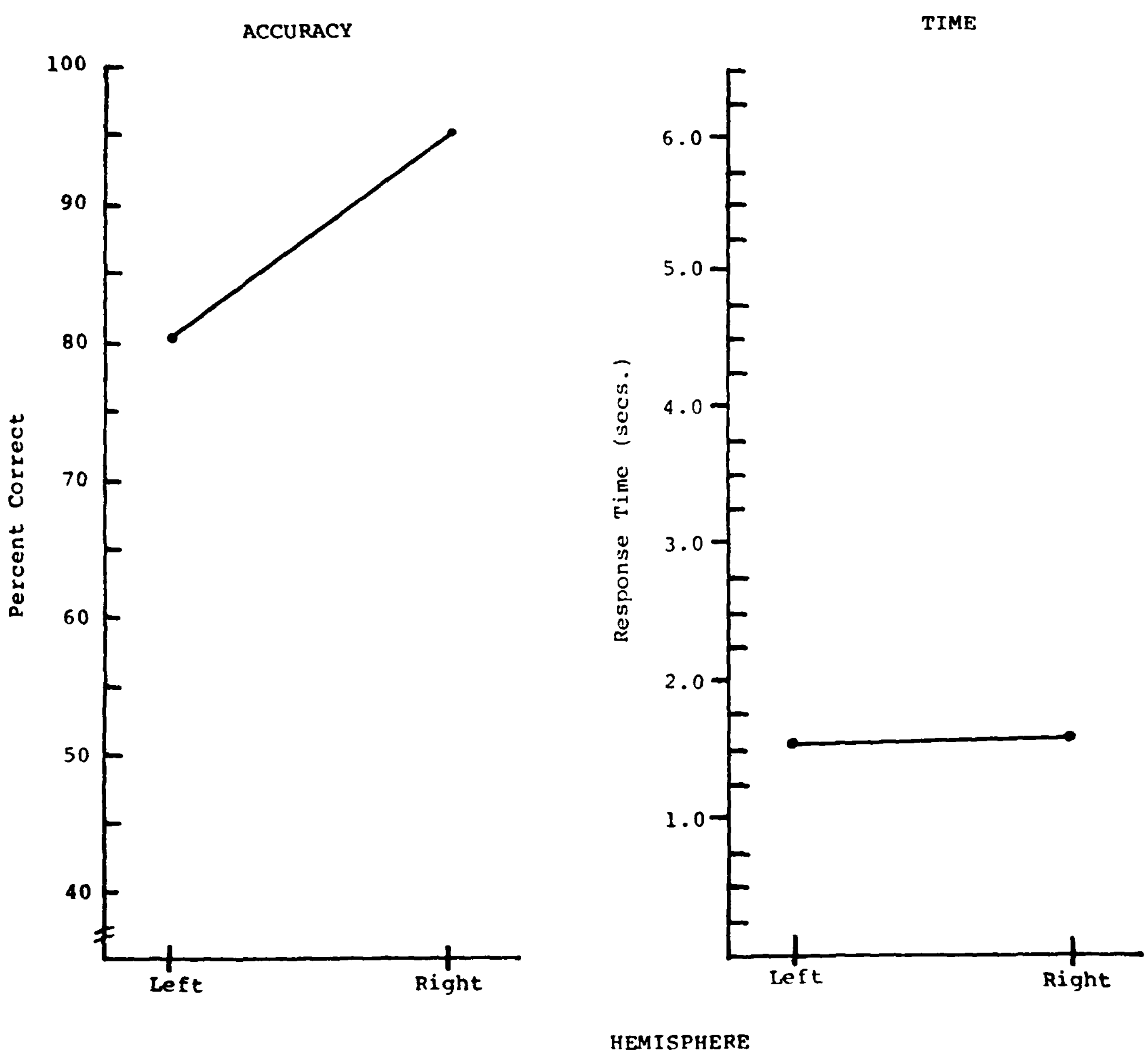
Results of Experiment 2. Perceptual analogue followed by imagery task.

Exp.3



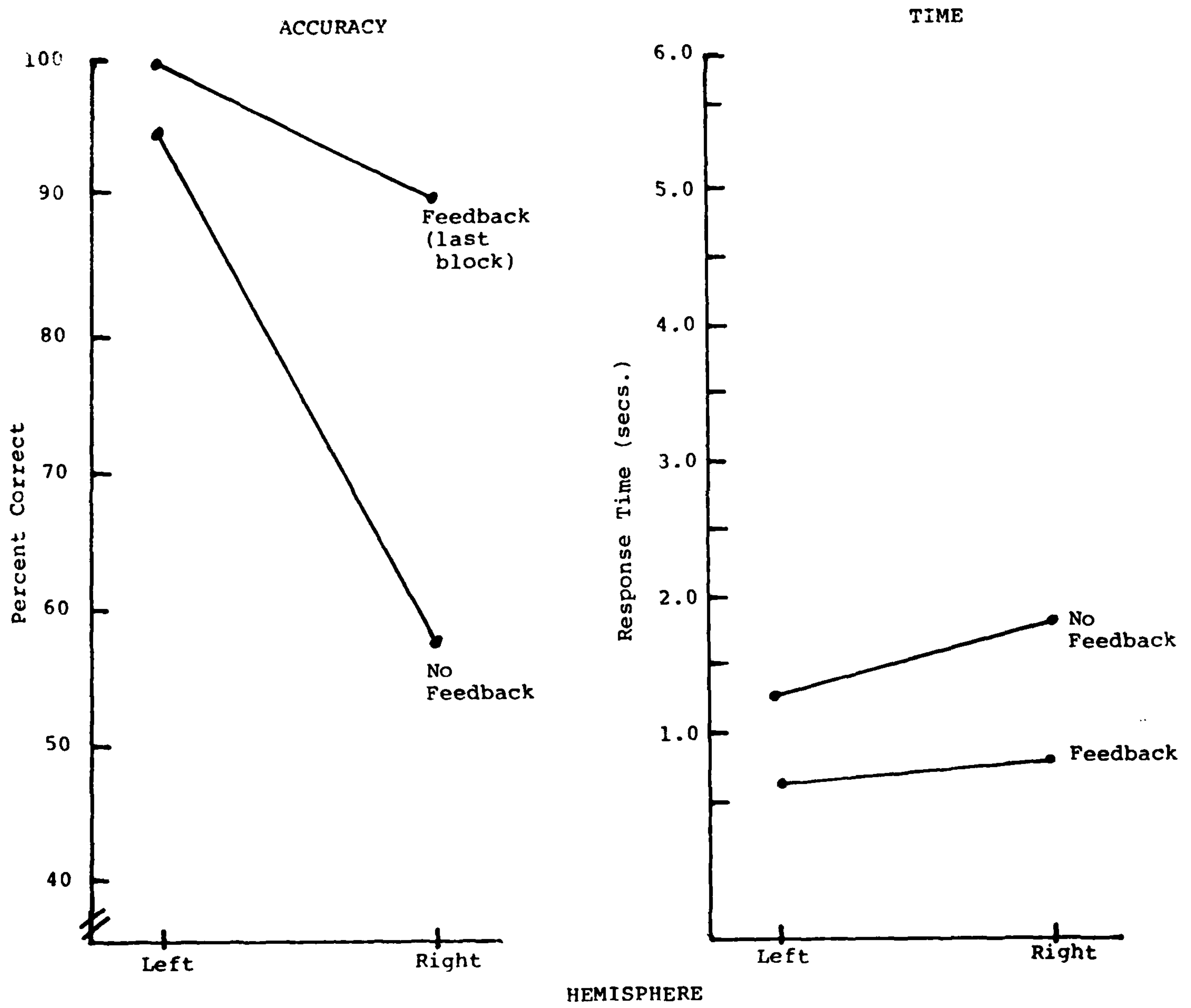
Results of Experiment 3, pointing response imagery task.

Exp. 4



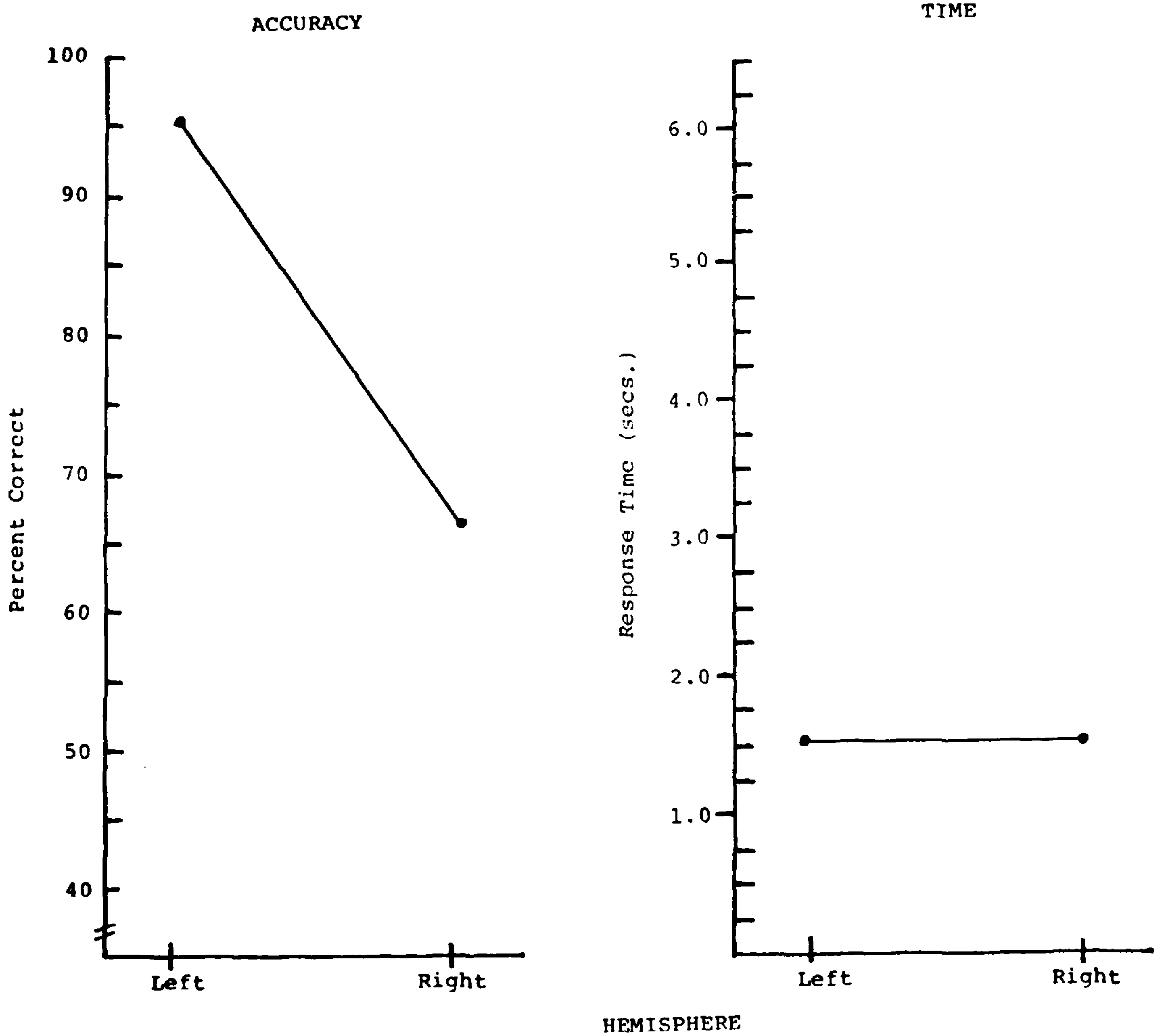
Results of Experiment 4, select and classify perceptual analogue.

Exp. 5A



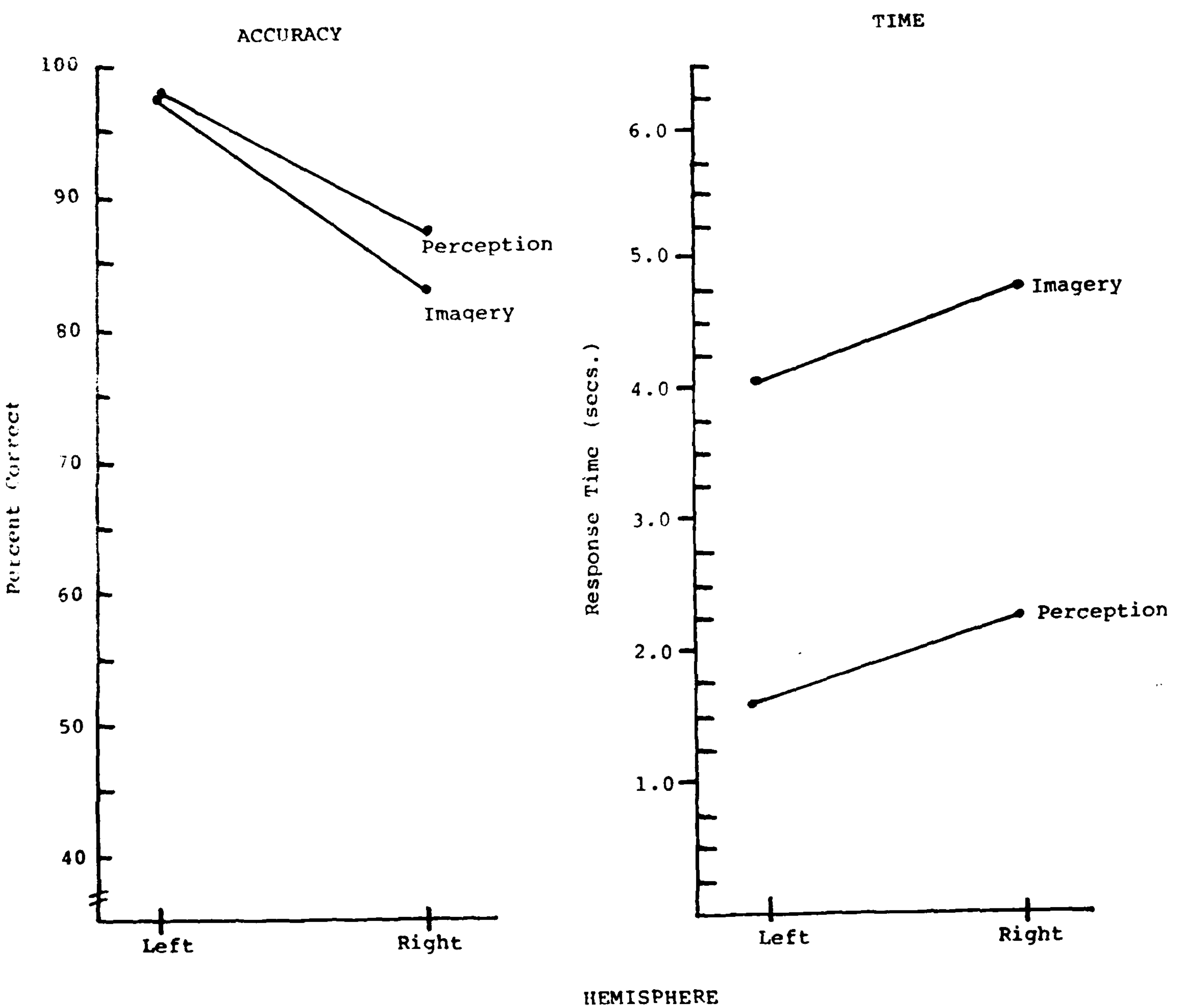
Results of Experiment 5. Initial and feedback imagery trials.

Exp. 5B



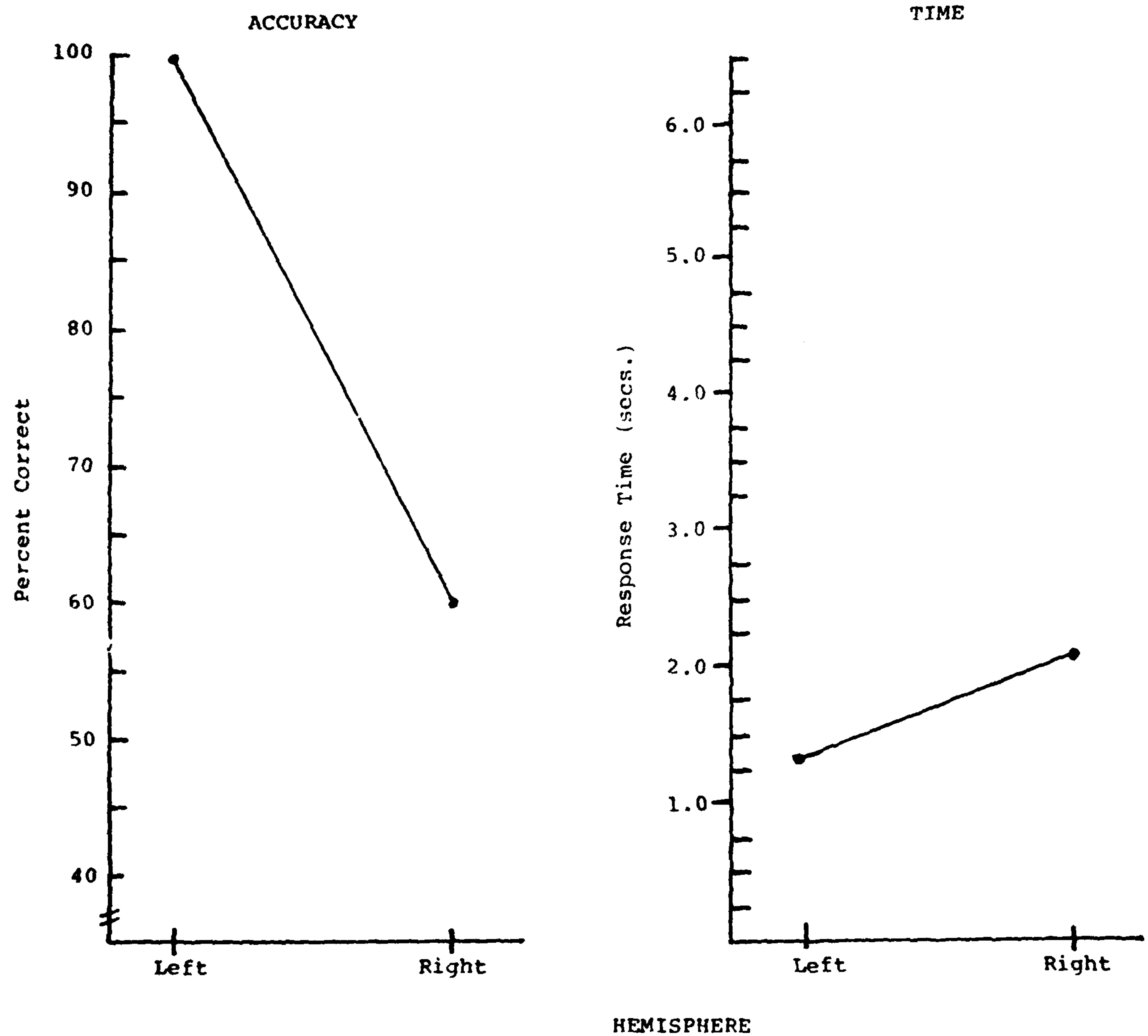
Results of Experiment 5. Transfer trials (no feedback).

Exp. 6A



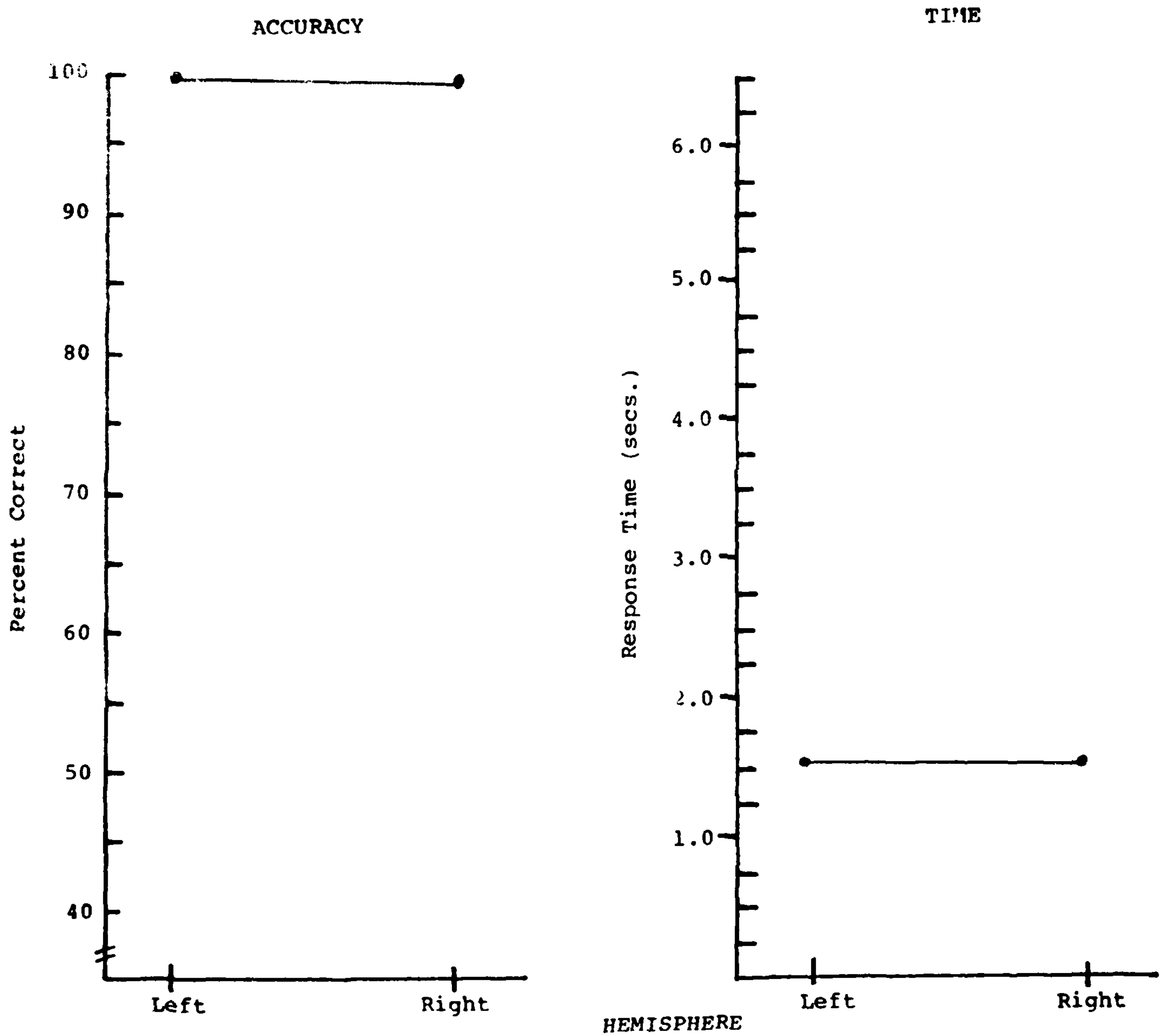
Results of Experiment 6, image retention and inspection and perceptual analogue.

Exp. 6B



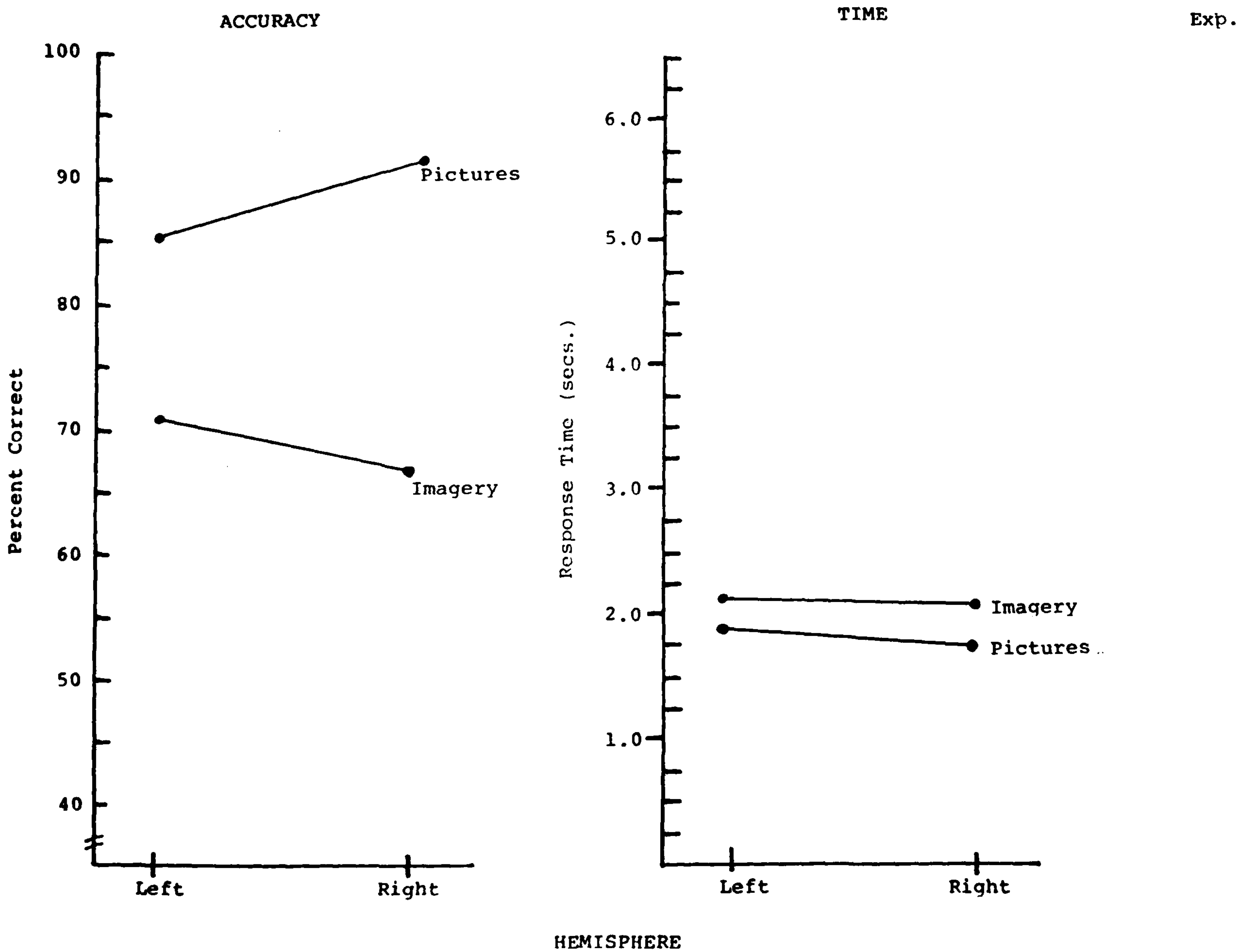
Experiment 6. Basic task follow up.

Exp. 7A

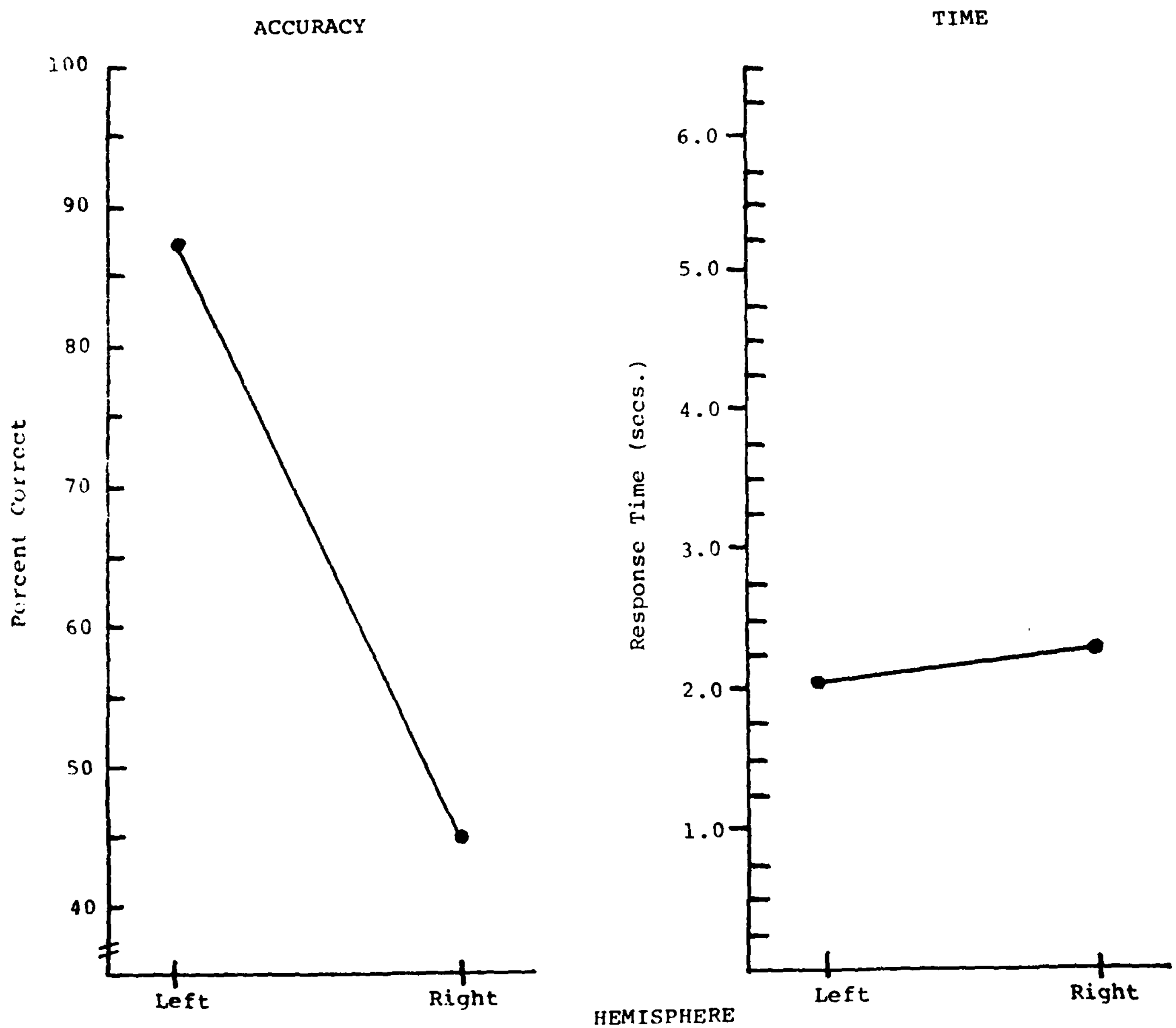


Results of close size comparisons. Experiment 7.

Exp. 7B

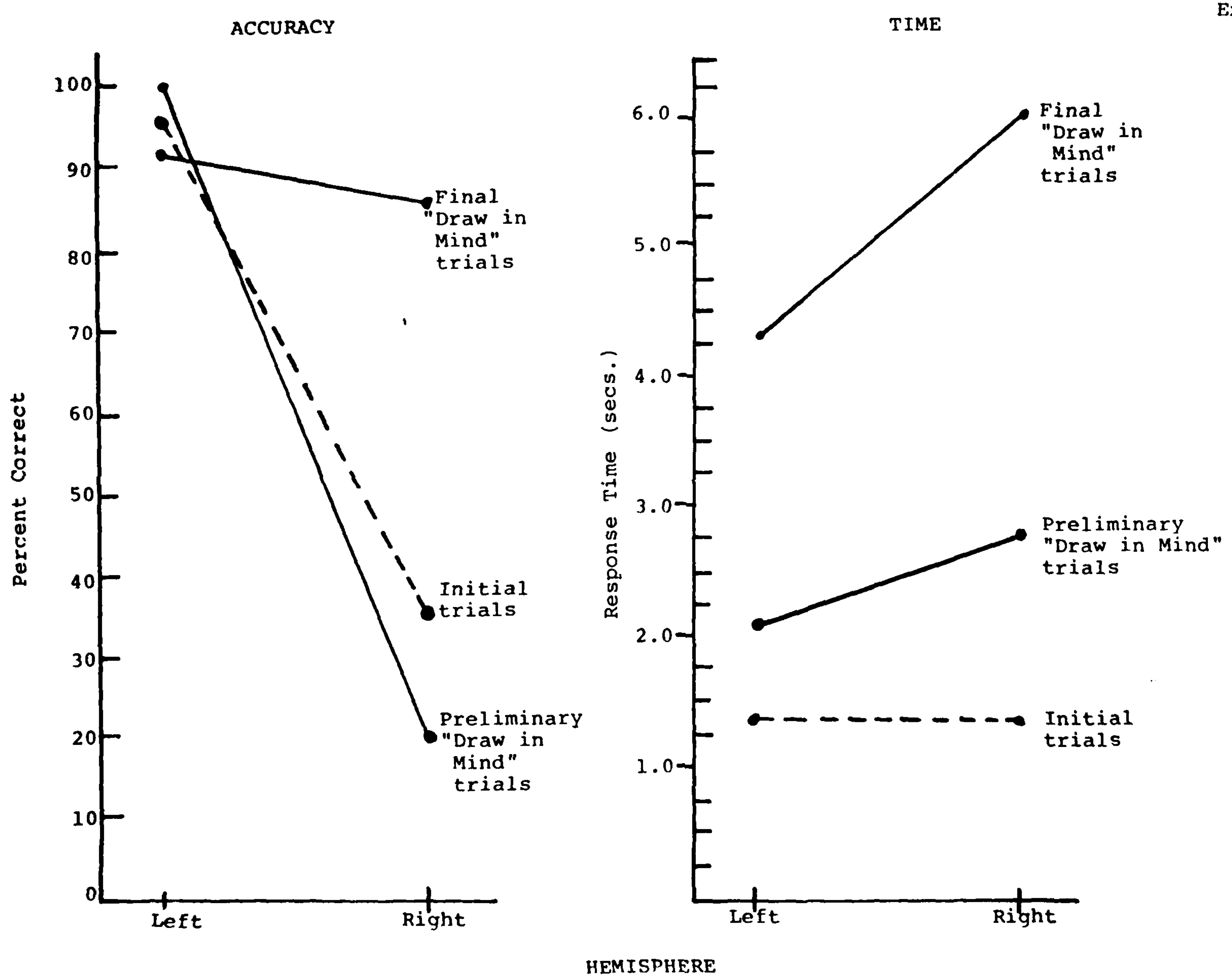


Results of height/width judgment in Experiment 7.



Results from Experiment 8, ears/skull judgment.

Exp. 9A.



Results from Experiment 9. Pre-drawing, initial drawing, and final drawing trials.

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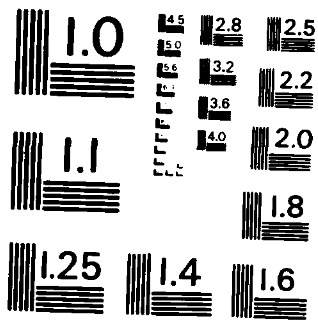
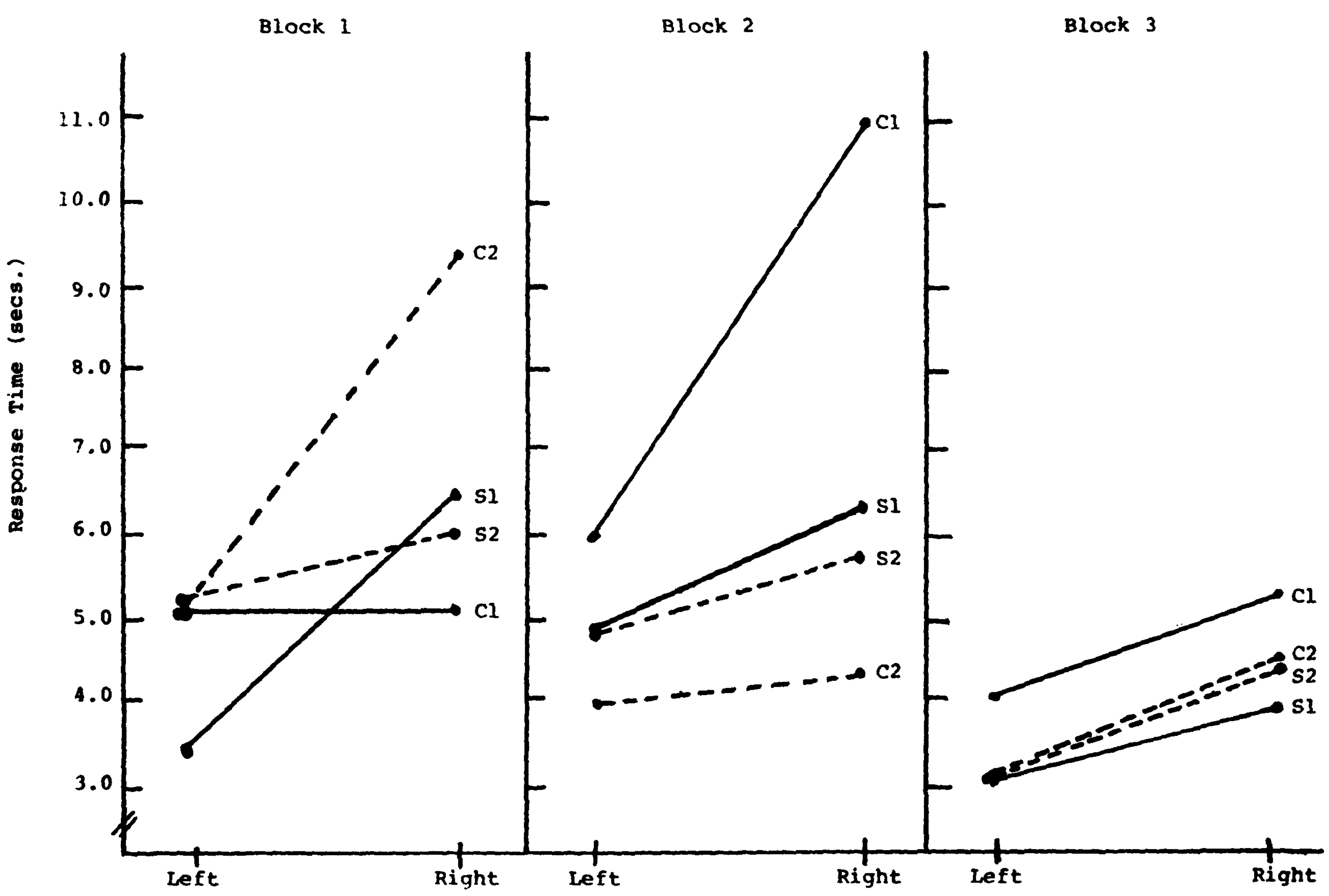


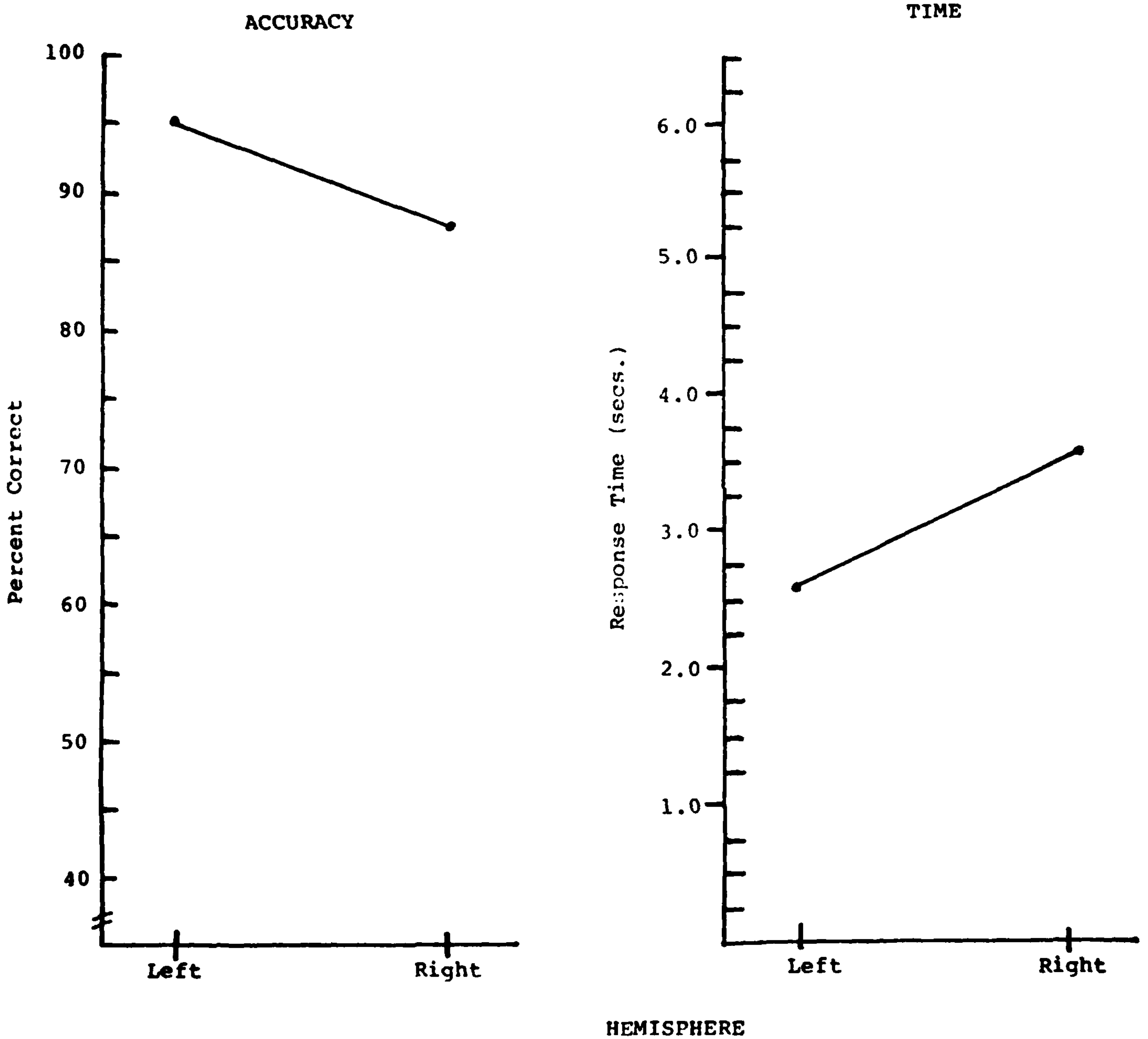
MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

Exp. 9B.



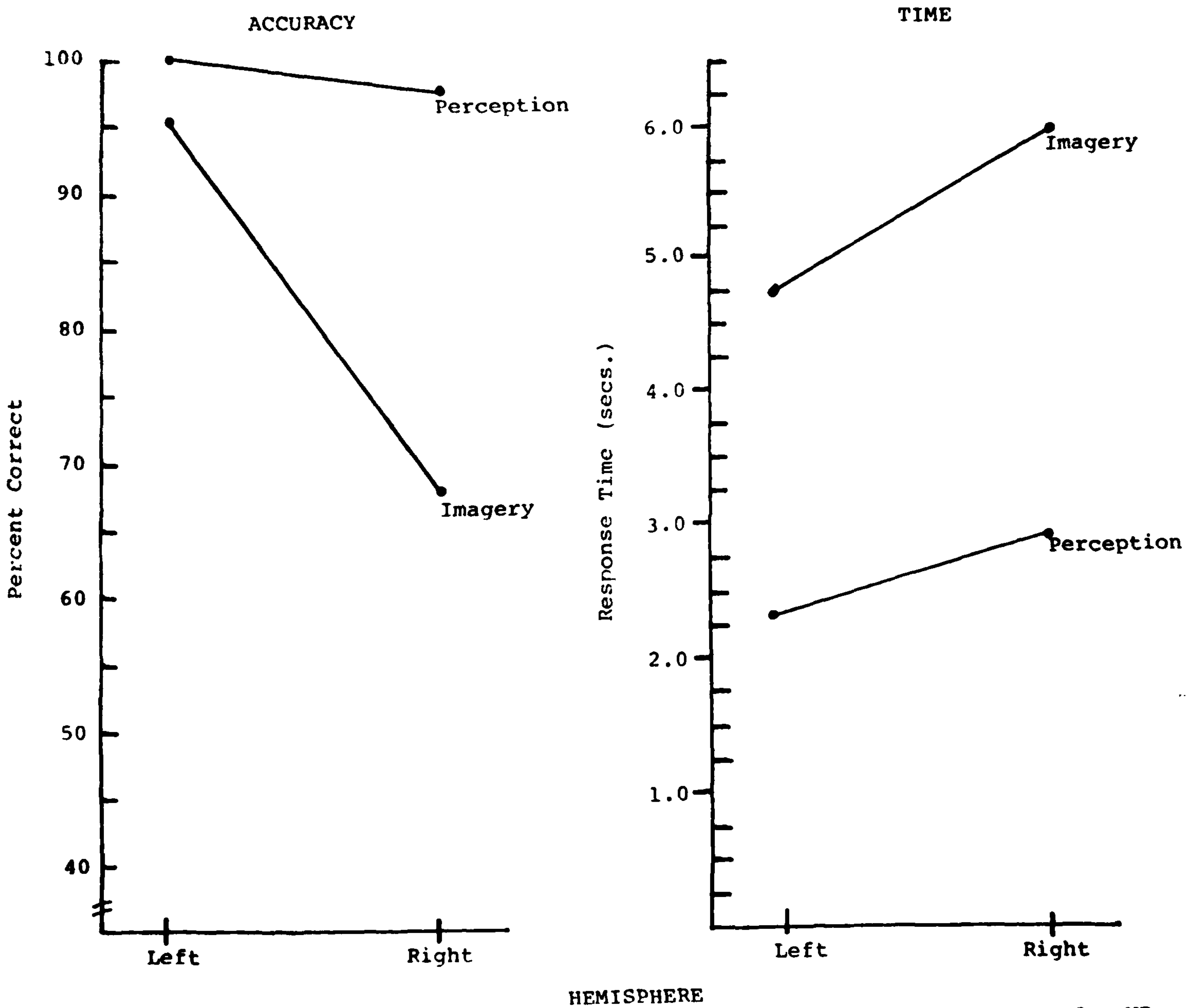
Results from Experiment 9. An interaction between hemisphere, block and stimulus type (straight=S, curved=C)

Exp. 9C.



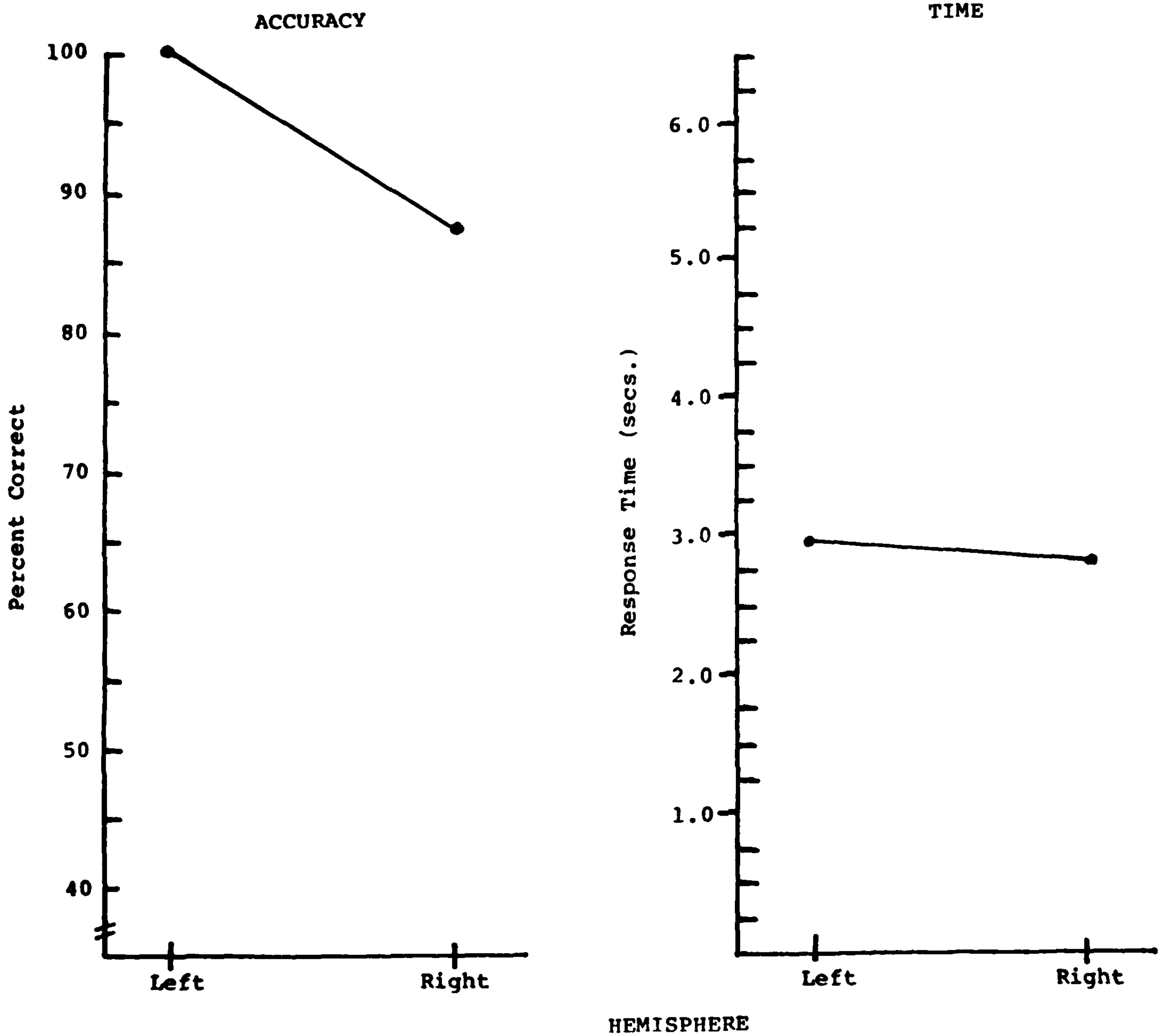
Results from Experiment 9. Transfer trials after "Draw in Mind" training.

Exp. 10A



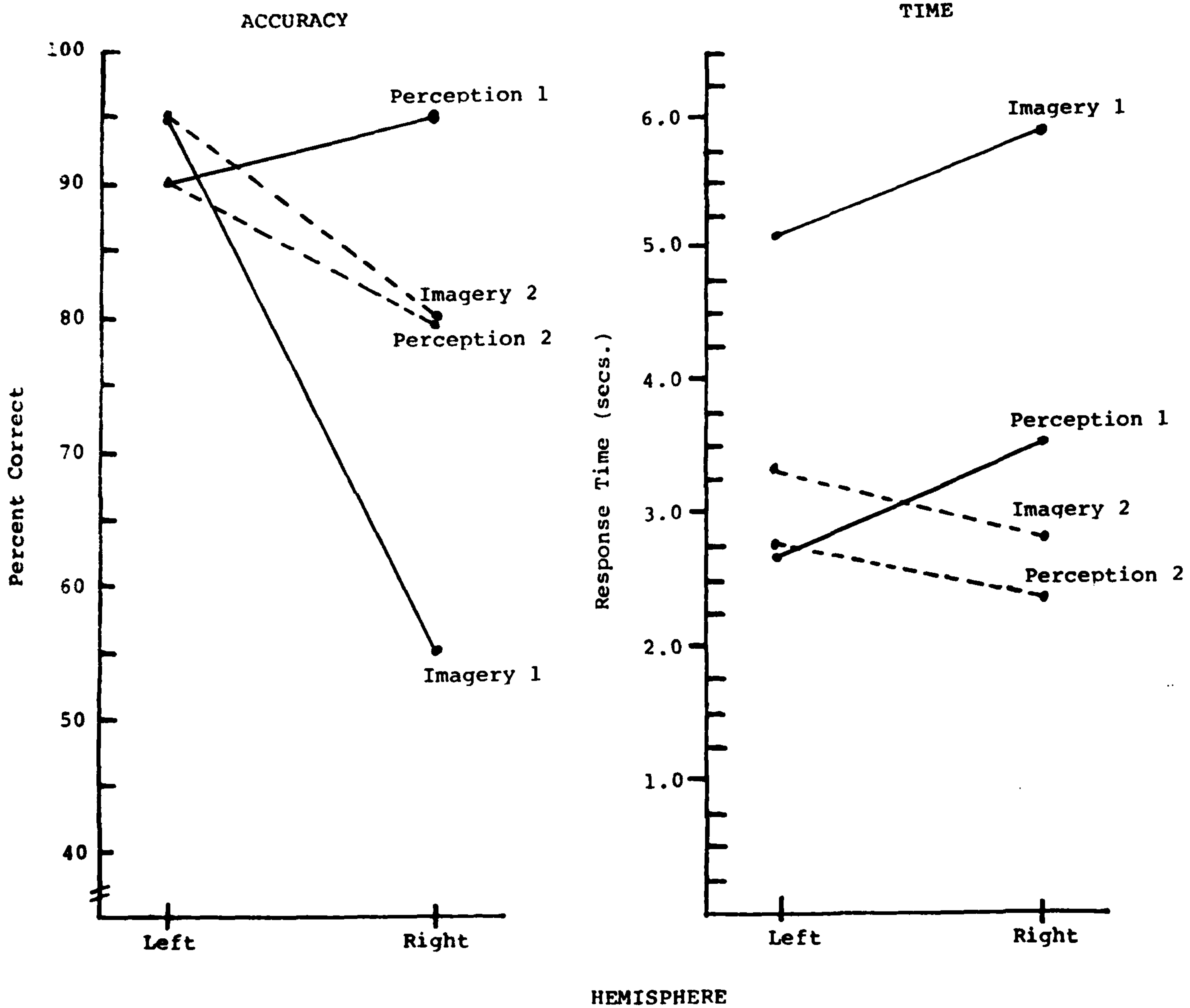
Results from Experiment 10. Basic imagery task and perceptual analogue for VP.

Exp. 10B



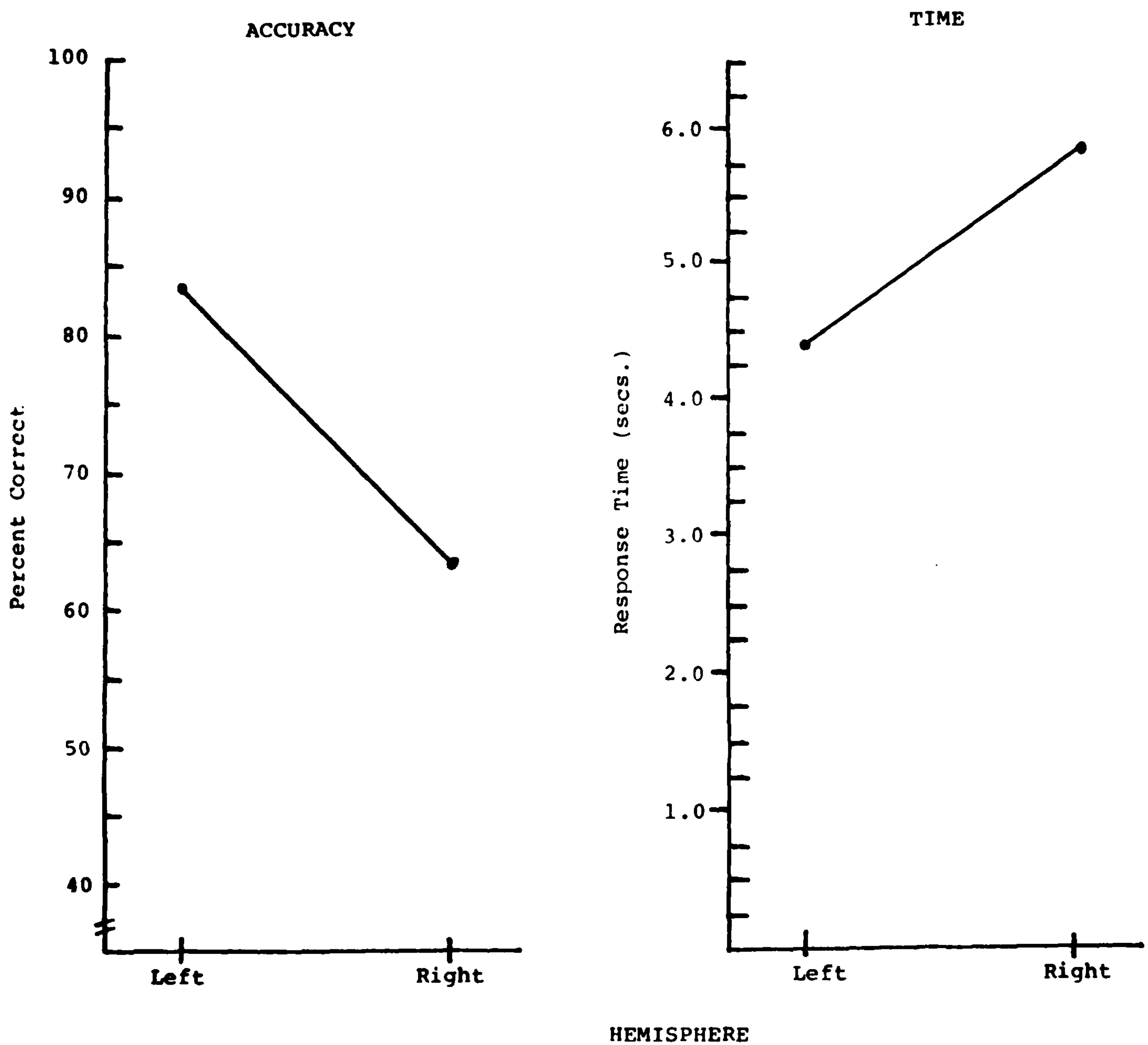
Results of Experiment 10. Last set of initial imagery trials.

Exp. 11.



Results from Experiment 11. Vertical-line-at-left judgments in imagery and perception.

Exp. 12.



Results of Experiment 12. Imagery transfer trials for VP.

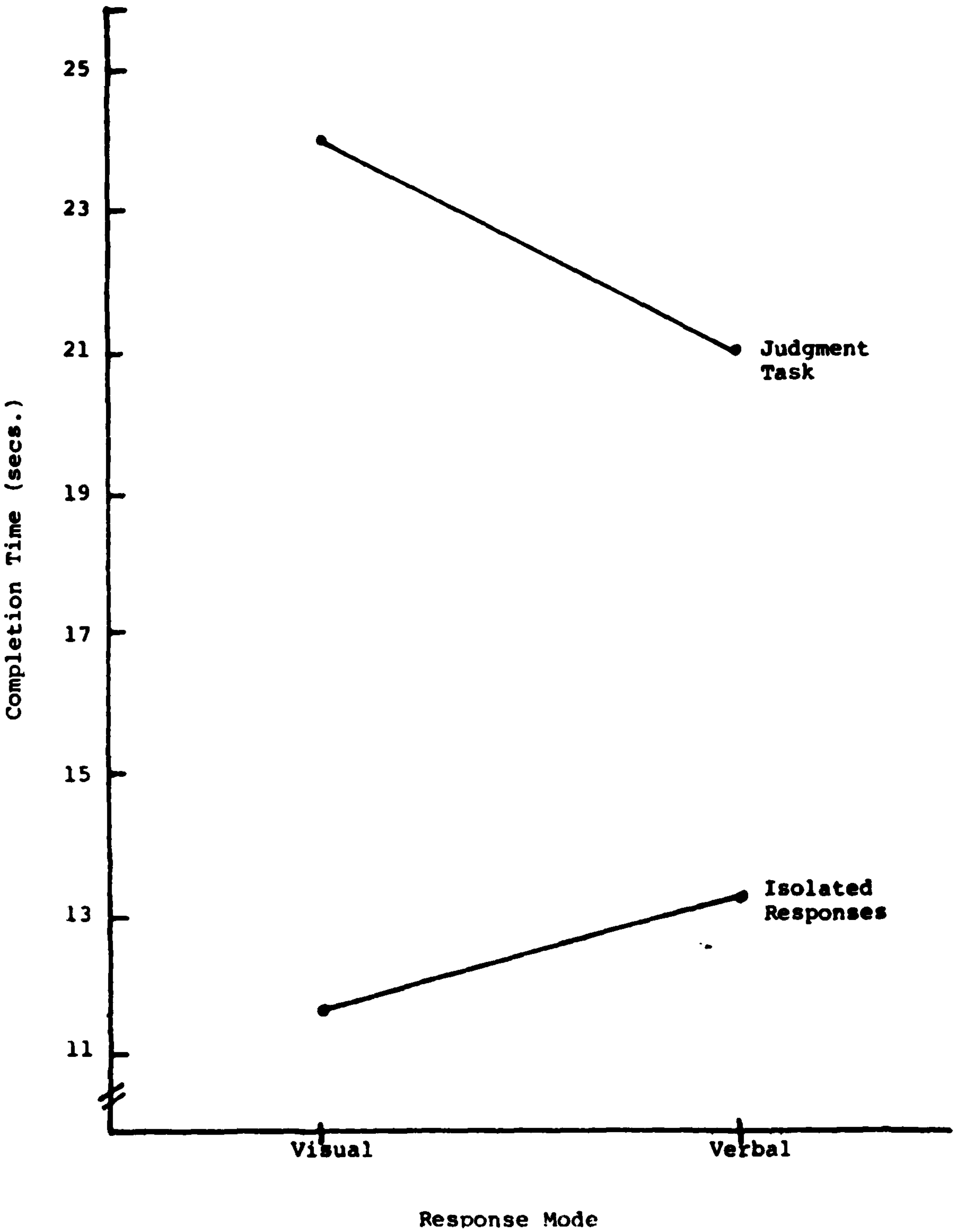


Figure 12. Image validation results.

Navy

1 Robert Ahlers
Code N711
Human Factors Laboratory
NAVTRAEQUIPCEN
Orlando, FL 32813

1 Dr. Meryl S. Baker
Navy Personnel R&D Center
San Diego, CA 92152

1 Dr. Alvah Bittner
Naval Biodynamics Laboratory
New Orleans, LA 70189

1 Dr. Nick Bond
Office of Naval Research
Liaison Office, Far East
APO San Francisco, CA 96503

1 Lt. Alexander Bory
Applied Psychology
Measurement Division
NAMRL
NAS Pensacola, FL 32508

1 Dr. Robert Breaux
NAVTRAEQUIPCEN
Code N-095R
Orlando, FL 32813

1 Dr. Robert Carroll
NAVOP 115
Washington , DC 20370

1 Dr. Susan Chipman
Code 442PT
Office of Naval Research
800 N. Quincy St.
Arlington, VA 22217

1 Dr. Stanley Collyer
Office of Naval Technology
800 N. Quincy Street
Arlington, VA 22217

1 CDR Mike Curran
Office of Naval Research
800 N. Quincy St.
Code 270
Arlington, VA 22217

Navy

1 Dr. Charles E. Davis
Personnel and Training Research
Office of Naval Research (Code 442PT)
800 North Quincy Street
Arlington, VA 22217

1 Dr. Marshall J. Farr
Director, Psychological Sciences
Office of Naval Research (Code 442)
800 North Quincy Street
Arlington, VA 22217

1 DR. PAT FEDERICO
Code P13
NPRDC
San Diego, CA 92152

1 Dr. Jim Hollan
Code 14
Navy Personnel R & D Center
San Diego, CA 92152

1 Dr. Ed Hutchins
Navy Personnel R&D Center
San Diego, CA 92152

1 Dr. Norman J. Kerr
Chief of Naval Technical Training
Naval Air Station Memphis (75)
Millington, TN 38054

1 Dr. William L. Maloy (02)
Chief of Naval Education and Training
Naval Air Station
Pensacola, FL 32508

1 Dr. James McBride
Navy Personnel R&D Center
San Diego, CA 92152

1 Dr William Montague
NPRDC Code 13
San Diego, CA 92152

1 Office of the Chief of Naval Operations
Research Development & Studies Branch
OP 115
Washington, DC 20350

1 LT Frank C. Petho, MSC, USN (Ph.D)
CNET (N-432)
NAS
Pensacola, FL 32508

Navy

1 Dr. Bernard Rimland (01C)
Navy Personnel R&D Center
San Diego, CA 92152

1 Dr. Carl Ross
CNET-PDCD
Building 90
Great Lakes NTC, IL 60088

1 Dr. Robert G. Smith
Office of Chief of Naval Operations
OP-987H
Washington, DC 20350

1 Dr. Alfred F. Smode
Senior Scientist
Code 7B
Naval Training Equipment Center
Orlando, FL 32813

1 Dr. Richard Sorensen
Navy Personnel R&D Center
San Diego, CA 92152

1 Dr. Frederick Steinheiser
CNO - OP115
Navy Annex
Arlington, VA 20370

1 Dr. Martin A. Tolcott
Leader, Psychological Sciences Division
Office of Naval Research
800 N. Quincy St.
Arlinsgon, VA 22217

1 Dr. James Tweeddale
Technical Director
Navy Personnel R&D Center
San Diego, CA 92152

1 Dr. Douglas Wetzel
Code 12
Navy Personnel R&D Center
San Diego, CA 92152

1 DR. MARTIN F. WISKOFF
NAVY PERSONNEL R& D CENTER
SAN DIEGO, CA 92152

1 Mr John H. Wolfe
Navy Personnel R&D Center
San Diego, CA 92152

Navy

1 Dr. Donald Woodward
Office of Naval Research (Code 441)
800 North Quincy Street
Arlington, VA 22217

1 Dr. Steven Zornetzer
Associate Director for Life Sciences
Office of Naval Research
800 N. Quincy St.
Arlington, VA 22217

Marine Corps

1 Jerry Lehnus
CAT Project Office
HQ Marine Corps
Washington , DC 20380

1 Major Frank Yohannan, USMC
Headquarters, Marine Corps
(Code MPI-20)
Washington, DC 20380

Army

1 Dr. Harold F. O'Neil, Jr.
Director, Training Research Lab
Army Research Institute
5001 Eisenhower Avenue
Alexandria, VA 22333

1 Commander, U.S. Army Research Institute
for the Behavioral & Social Sciences
ATTN: PERI-BR (Dr. Judith Orasanu)
5001 Eisenhower Avenue
Alexandria, VA 22333

1 Dr. Ray Perez
5001 Eisenhower Avenue
PERI-II
Alexandria, VA 22333

1 Joseph Psotka, Ph.D.
ATTN: PERI-1C
Army Research Institute
5001 Eisenhower Ave.
Alexandria, VA 22333

1 Dr. Robert Sasmor
U. S. Army Research Institute for the
Behavioral and Social Sciences
5001 Eisenhower Avenue
Alexandria, VA 22333

1 Dr. Joyce Shields
Army Research Institute for the
Behavioral and Social Sciences
5001 Eisenhower Avenue
Alexandria, VA 22333

1 Dr. Hilda Wing
Army Research Institute
5001 Eisenhower Ave.
Alexandria, VA 22333

Air Force

1 Dr. Earl A. Alluisi
HQ, AFHRL (AFSC)
Brooks AFB, TX 78235

1 Mr. Raymond E. Christal
AFHRL/MOE
Brooks AFB, TX 78235

1 Dr. Alfred R. Fregly
AFOSR/NL
Bolling AFB, DC 20332

1 Dr. Genevieve Haddad
Program Manager
Life Sciences Directorate
AFOSR
Bolling AFB, DC 20332

1 Dr. Patrick Kyllonen
AFHRL/MOE

Brooks AFB, TX 78235

1 Dr. Roger Pennell
Air Force Human Resources Laboratory
Lowry AFB, CO 80230

1 Dr. Malcolm Ree
AFHRL/MP
Brooks AFB, TX 78235

1 Dr. Joseph Yasatuke
AFHRL/LRT
Lowry AFB, CO 80230

Department of Defense

1 Dr. Craig I. Fields
Advanced Research Projects Agency
1400 Wilson Blvd.
Arlington, VA 22209

1 Dr. W. Steve Sellman
Office of the Assistant Secretary
of Defense (MRA & L)
2B269 The Pentagon
Washington, DC 20301

1 Major Jack Thorpe
DARPA
1400 Wilson Blvd.
Arlington, VA 22209

1 Dr. Robert A. Wisher
OUSDRE (ELS)
The Pentagon, Room 3D129
Washington, DC 20301

Civilian Agencies

1 Dr. Helen J. Christup
Office of Personnel R&D
1900 E St., NW
Office of Personnel Management
Washington, DC 20015

1 Dr. Arthur Melmed
724 Brown
U. S. Dept. of Education
Washington, DC 20208

1 Dr. Andrew R. Molnar
Office of Scientific and Engineering Personnel and Education
National Science Foundation
Washington, DC 20550

1 Dr. David Pearl
Room 10-C-09
5600 Fishers Lane
Rockville, MD 20857

1 Dr. Joseph L. Young, Director
Memory & Cognitive Processes
National Science Foundation
Washington, DC 20550

Private Sector

1 Dr. John R. Anderson
Department of Psychology
Carnegie-Mellon University
Pittsburgh, PA 15213

1 Dr. Isaac Bejar
Educational Testing Service
Princeton, NJ 08450

1 Dr. Pat Carpenter
Department of Psychology
Carnegie-Mellon University
Pittsburgh, PA 15213

1 Dr. John B. Carroll
409 Elliott Rd.
Chapel Hill, NC 27514

1 Dr. Lynn A. Cooper
LRDC
University of Pittsburgh
3939 O'Hara Street
Pittsburgh, PA 15213

1 Dr. Emmanuel Donchin
Department of Psychology
University of Illinois
Champaign, IL 61820

1 Dr. Jeffrey Elman
University of California, San Diego
Department of Linguistics
La Jolla, CA 92093

1 Dr. Susan Embertson
PSYCHOLOGY DEPARTMENT
UNIVERSITY OF KANSAS
Lawrence, KS 66045

1 Dr. Anders Ericsson
Department of Psychology
University of Colorado
Boulder, CO 80309

1 Dr. Dexter Fletcher
University of Oregon
Department of Computer Science
Eugene, OR 97403

1 Dr. John R. Frederiksen
Bolt Beranek & Newman
50 Moulton Street
Cambridge, MA 02138

Private Sector

1 Dr. Don Gentner
Center for Human Information Processing
University of California, San Diego
La Jolla, CA 92093

1 Dr. Robert Glaser
Learning Research & Development Center
University of Pittsburgh
3939 O'Hara Street
PITTSBURGH, PA 15260

1 Dr. Daniel Gopher
Faculty of Industrial Engineering
& Management
TECHNION
Haifa 32000
ISRAEL

1 Dr. Henry M. Halff
Halff Resources
4918 33rd Road, North
Arlington, VA 22207

1 Dr. Earl Hunt
Dept. of Psychology
University of Washington
Seattle, WA 98105

1 Dr. Marcel Just
Department of Psychology
Carnegie-Mellon University
Pittsburgh, PA 15213

1 Dr. Demetrios Karis
Department of Psychology
University of Illinois
603 E. Daniel Street
Champaign, IL 61820

1 Dr. Steven W. Keele
Dept. of Psychology
University of Oregon
Eugene, OR 97403

1 Dr. Scott Kelso
Haskins Laboratories, Inc
270 Crown Street
New Haven, CT 06510

1 Dr. Stephen Kosslyn
1236 William James Hall
33 Kirkland St.
Cambridge, MA 02138

Private Sector

1 Dr. Marcy Lansman
The L. L. Thurstone Psychometric
Laboratory
University of North Carolina
Davie Hall 013A
Chapel Hill, NC 27514

1 Dr. Michael Levine
Department of Educational Psychology
210 Education Bldg.
University of Illinois
Champaign, IL 61801

1 Dr. Don Lyon
P. O. Box 44
Higley , AZ 85236

1 Dr. Jay McClelland
Department of Psychology
MIT
Cambridge, MA 02139

1 Dr. Allen Munro
Behavioral Technology Laboratories
1845 Elena Ave., Fourth Floor
Redondo Beach, CA 90277

1 Dr. Donald A Norman
Cognitive Science, C-015
Univ. of California, San Diego
La Jolla, CA 92093

1 Dr. James W. Pellegrino
University of California,
Santa Barbara
Dept. of Psychology
Santa Barabara , CA 93106

1 Dr. Mike Posner
Department of Psychology
University of Oregon
Eugene, OR 97403

1 Dr. Andrew M. Rose
American Institutes for Research
1055 Thomas Jefferson St. NW
Washington, DC 20007

1 Dr. David Rumelhart
Center for Human Information Processing
Univ. of California, San Diego
La Jolla, CA 92093

Private Sector

1 PROF. FUMIKO SAMEJIMA
DEPT. OF PSYCHOLOGY
UNIVERSITY OF TENNESSEE
KNOXVILLE, TN 37916

1 Dr. Arthur Samuel
Yale University
Department of Psychology
Box 11A, Yale Station
New Haven, CT 06520

1 Dr. Walter Schneider
Psychology Department
603 E. Daniel
Champaign, IL 61820

1 Dr. David Shucard
Brain Sciences Laboratories
Department of Pediatrics
National Jewish Hospital & Research Ctr
3800 E. Colfax Ave.
Denver, CO 80206

1 Dr. H. Wallace Sinaiko
Program Director
Manpower Research and Advisory Services
Smithsonian Institution
801 North Pitt Street
Alexandria, VA 22314

1 Dr. Kathryn T. Spoehr
Psychology Department
Brown University
Providence, RI 02912

1 Dr. Robert Sternberg
Dept. of Psychology
Yale University
Box 11A, Yale Station
New Haven, CT 06520

1 Dr. Perry W. Thorndyke
Perceptronics, Inc.
545 Middlefield Road, Suite 140
Menlo Park, CA 94025

1 Dr. Douglas Towne
Univ. of So. California
Behavioral Technology Labs
1845 S. Elena Ave.
Redondo Beach, CA 90277

Private Sector

1 Dr. Keith T. Wescourt
Perceptronics, Inc.
545 Middlefield Road, Suite 140
Menlo Park, CA 94025

1 Dr. Christopher Wickens
Department of Psychology
University of Illinois
Champaign, IL 61820